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ENERGY EFFICIENT RECONFIGURABLE MAC PROTOCOL FOR UNDERWATER ACOUSTIC SENSOR NETWORK

by

Khaja Mohammad Shazzad

A Dissertation

Submitted to the Faculty of Graduate Studies
through the Department of Electrical and Computer Engineering
in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada

2015

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Energy Efficient Reconfigurable MAC Protocol for Underwater Acoustic Sensor Network

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Declaration of Co-Authorship/Previous Publication

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

This thesis contains the outcome of a research undertaken by me under the supervision of Dr. K. E. Tepe and Dr. Esam Abdel-Raheem. The collaboration is covered in Chapters 2, 3, and 4 of the thesis. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of co-authors was primarily through the provision of valuable suggestions and helping in comprehensive analysis of the experimental results submitted for publication.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have permission from each of the co-author(s) to include the above material(s) in my thesis. I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

II. Declaration of Previous Publication

This thesis includes two original papers that have been previously published/submitted for publication in peer reviewed conference, as follows:

Thesis Chapter	Publication title/full citation	Publication status
Chapters 2 and 3	Khaja Shazzad, Kemal Tepe and Esam Abdel-Raheem “ <i>Multi-hop Enabled Energy Efficient MAC Protocol for Underwater Acoustic Sensor Networks</i> ”, Journal of Sensor and Actuator Networks	Second phase reviews are received. The updated paper is to be submitted soon for the next review phase.
Chapters 2 and 4	Khaja Shazzad, Kemal Tepe and Esam Abdel-Raheem “ <i>Towards Building a Common Framework of MAC and PHY Layers’ Simulation of Underwater Acoustic Sensor Networks</i> ”	To be submitted

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Abstract

In a multi-hop Underwater Acoustic Sensor Network (UWASN) the challenges of the medium access control (MAC) are different than that of single hop fully connected network. Existing MAC solutions try to solve the challenges of MAC control by channel reservation or contention elimination techniques. These techniques heavily depend on the transmissions of control packets that result in large overhead specially in terms of energy consumptions. In this thesis, a multi-hop enabled energy efficient MAC protocol for UWASN is proposed by exploiting a novel 2-phase contention resolution technique that minimizes the usage of control packets by utilizing short duration tones. A probabilistic model of the proposed protocol is also developed to analyze the performance of the protocol analytically. A network simulation framework has been designed to simulate MAC and a physical layer for UWASN. The proposed MAC protocol has been evaluated through quantitative analysis and simulation. By evaluating this proposed protocol through quantitative analysis and simulation, this research found that the proposed protocol outperforms in terms of energy efficiency, channel utilization and end-to-end delay. The proposed protocol achieves stable throughput and a maximum 30% of theoretical maximum channel utilization in high traffic load in comparison to the existing protocol that becomes unstable and does not perform well. Additionally, the proposed protocol achieves better energy efficiency and lower end-to-end delay.

To my parents, wife *Jaheda* and children *Afra*, *Talha* and *Zahra*.

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List of Abbreviations

ARP	Address Resolution Protocol
CA	Collision Avoidance
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CR	Contention Round
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
CTD	conductivity,temperature and depth
CTS	Clear To Send
DSP	Digital Signal Processor
ECS	Efficient Communication Scheduling
EE-MAC	Energy Efficient MAC
ESFRA	Extended Sliding Frame Reservation ALOHA
FAMA	Floor Acquisition Multiple Access
FAMA-NCS	FAMA Non-persistent Carrier Sensing
GloMoSim	Global Mobile Information System Simulator
GNU	GNU's Not Unix
GPL	GNU General Public License
GSM	Global System for Mobile Communications
IDE	Integrated Development Environment

IEEE	The Institute of Electrical and Electronic Engineers
MACAW	Multiple Access with Collision Avoidance for Wireless
MAC	Medium Access Control
MEEMAC	Multihop Enabled Energy Efficient MAC
MILP	Mixed Integer Linear Programming
MiXiM	Mixed Simulator
MobNet	Mobile Network
NED	Network Description
NIC	Network Interface Card
OOP	Object Oriented Programming
OSI	Open Systems Interconnection
PHY	Physical
RF	Radio Frequency
RP	Reservation Period
RSSI	Received Signal Strength Indicator
RTS	Request To Send
S-FAMA	Slotted FAMA
S-MAC	Sensor MAC
SRMA	Split-Channel Reservation Multiple Access
ST-CG	Spatial-Temporal Conflict Graph
TDMA	Time Division Multiple Access
T-LOHI	Tone LOHI
TOTA	Trac-based One-step Trial Approach
UWASN	Underwater Acoustic Sensor Network
WHOI	Woods Hole Oceanographic Institution
WSN	Wireless Sensor Network
XML	Extensible Markup Language

Chapter 1

Introduction

1.1 Motivation

The first underwater communications occurred between submarines during World War II [48]. Since those nascent forms of underwater communications began the demand for more reliable underwater communication systems and networks have been steadily increasing. The result of the research in this field now manifests itself in applications for; exploring underwater resources; natural and man-made disaster prevention and forecasting; underwater environment and marine habitat monitoring; as well as military and commercial surveillance, etc. [51, 53, 4, 26, 41]. Most of these traditional oceanographic techniques use different type of sensors for monitoring physical phenomenon under the oceans surface. Sensors are deployed to monitor the ocean bottom and ocean-column and record the data inside sensor hardware. After a fixed period of monitoring, these deployed sensors are recovered for data analysis. These techniques have many drawbacks. The data gathered, for instance, is outdated and also cannot be used for on-line decision making. As well, once the sensors are configured they cannot be reconfigured during the mission. Another issue is that sensor failure, during monitoring period, can not be detected. After recovery of the sensors it can transpire that no useful data was recorded due to hardware or software failures. Moreover, due to limited in-sensor storage, sensors cannot store enough data

for appropriate analysis. Additionally, physical phenomenon cannot be monitored over an extended period of time. Underwater acoustic sensor networks (UWASN) offer an alternative to traditional sensors as they can eliminate the above mentioned drawbacks. They have been successfully applied in oceanography, distributed tactical surveillance, habitat and environment monitoring, underwater oilfields or reservoirs exploration, disaster prevention, and mine reconnaissance, etc. [51, 53, 4, 26, 41]. The next generation underwater communication systems must be rethought and redesigned to ensure efficient, effective and reconfigurable systems that are also cost effective.

Several novel research challenges are introduced to many potential applications of underwater sensor networks, unlike in terrestrial wireless sensor networks. Optical communication provides one option for underwater communications but it has critical restrictions as it is viable only in extremely clear water and for a very short range [49, 17, 65, 17]. Acoustic communication, therefore, is the only feasible option for an underwater network. However, since radio waves experience strong attenuation, they are applicable in only very short range communication and experience a high absorption rate in underwater communications [10, 13]. Moreover, acoustic communication inherently shows a long propagation delay (in the order of five magnitudes higher than for radio frequencies, RF) [30, 49, 17, 19, 54]. Thus, the underwater acoustic channel exhibits severe multi-path fading, Doppler spreading and space-time uncertainty, which cause a high bit error rate. It is also restricted to produce a low data rate. Underwater acoustic networks must be energy efficient because the battery power of the modem is limited and the battery cannot be recharged. Underwater sensors are also prone to failures because of fouling and corrosion [52, 51, 43, 12, 13].

While an underwater acoustic communication system seems to provide a viable option its use currently has critical restrictions. For example, the energy required for transmission compared to that of reception is in several orders of magnitude [55]. Consequently, transmitted packet collisions not only reduce the channel utilization but also cause precious energy loss. Energy efficiency is critical for UWASN since the underwater sensors operate on batteries. The lifetime of sensors deployed underwater mainly depend on the consump-

tion of energy by the sensors transmission module. UWASN is usually deployed over a large area underwater and sensors are arrayed such that multi-hop communication is the required option. In [43], it was shown that multi-hop communication is more energy-efficient than single hop communication.

In order to provide a robust, scalable, and stable UWASN technology, research in the area has to address these challenges while providing an optimum solution. In each layer of the OSI Reference Model [71], there are number of research activities being carried out to mitigate those challenges and to develop robust and practical solutions for UWASN. This research focuses on the MAC layer protocol design for multi-hop UWASN. MAC protocols are very important, and are considered to be one of the most challenging elements of UWASNs as they have the capacity to provide contention free and efficient networking. Furthermore, multi-hop networking is the preferred option not only for covering a vast area of the sea bed for monitoring purposes, but also to ensure energy efficiency [43].

1.2 Research Problem

In a multi-hop distributed acoustic sensor network, the challenges in the MAC layer are different from in a single hop fully connected network. In a multi-hop scenario, collisions between frames being transmitted are caused by two different groups of nodes- interfering and hidden. Existing MAC solutions try to resolve those collisions in a single reservation or by using contention elimination techniques. For examples, S-FAMA [37] and others MACAW-based [7] MAC protocols eliminated collisions caused by interfering and hidden nodes through a single RTS/CTS (Request to Send/Clear to Send) cycle, which can be called a monolithic reservation because RTS and CTS control packets are used to eliminate both interfering nodes and hidden nodes simultaneously from channel contention in a single reservation period. This reservation mechanism requires large overhead especially in terms of energy consumption. That is why, this mechanism is not suitable for underwater acoustic sensor networks where energy conservation is the most important requirement.

The research presented here, therefore, has segregated this contention resolution into two different phases and proposes a novel two-phase contention resolution technique. This technique enables multi-hop communications while reducing energy overhead, providing high and stable throughput, as well as shortening end-to-end delay. In the first phase, interfering contending nodes are eliminated using short tone exchanges, then in the next phase RTS and CTS are utilized to reserve the channel only to eliminate collision due to contending hidden nodes. This two-phased reservation provides several performance and design benefits. These include energy savings due to both low power tone utilization instead of control packets and collision avoidance from hidden nodes, higher channel utilization, lower effective end-to-end delay, modular architecture, ease of implementation, adaptation, and reconfiguration depending on the traffic types, loads and network topology.

The main objective of this research is to design a MAC protocol for multi-hop UWASNs fulfilling the following goals:

Efficient Channel Utilization: It should provide high and stable channel utilization.

Low Energy Consumption: The overall energy consumption for the protocol should be minimized.

Effective Collision Avoidance: It should provide effective collision avoidance in order to reduce the data packet loss.

Scalable to Large Numbers of Nodes: It should be scalable; the protocol should behave in a consistent manner irrespective to the number of nodes in the network.

Reconfigurable: The protocol should provide the means of reconfiguration according to traffic load and network topology.

1.3 Contribution and Results

The contributions of this thesis are as follows:

1. This research has proposed a novel multi-hop-enabled energy efficient MAC layer protocol for UWASN that also provides stable and high throughput compared to existing protocols.
2. This research has also developed a probabilistic model of the proposed protocol in order to analyze the proposed protocol.
3. The research has conducted the design and the development of a simulation testbed in order to simulate MAC and a physical layer for UWASN.
4. This research has implemented the proposed protocol and two other competing protocols in the developed network simulation environment and performed extensive simulations to analyze and evaluate its performance against competing existing protocols.

By evaluating this proposed protocol through quantitative analysis and simulation, this research found that the proposed protocol outperforms existing competing protocols in terms of energy efficiency, channel utilization and end-to-end delay. The proposed protocol achieves stable throughput and a maximum 30% of theoretical maximum channel utilization in high traffic loads in comparison to the existing protocols that become unstable and do not perform well. Additionally, the proposed protocol achieves better energy efficiency (at least one order of magnitude) and lower end-to-end delay (at several orders of magnitude). This thesis presents a comparison between the simulation and analytical results, and notes that the simulation results are in congruence with the analytical results.

1.4 Organization of the Thesis

This thesis is organized in the following manner. Chapter 2 provides a literature review on existing MAC approaches and challenges corresponding to MAC protocol design in UWASNs. An introduction to the UWASN simulation environment is also described in

Chapter 2. Chapter 3 presents an in-depth description of the proposed protocol, which will be referred as Multihop Enabled Energy Efficient MAC (MEEMAC) protocol from here on. Chapter 3 also presents a probabilistic model of the proposed protocol. The model is utilized to calculate channel utilization, energy consumption and end-to-end delay for a specified network topology. Chapter 4 describes the design of MAC and PHY layers for UWASNs simulation exploiting the MiXiM framework. Chapter 5 provides a discussion about the simulation environment, simulation results as well as an evaluation of the proposed protocol with existing MAC protocols based on simulation results. The conclusion and a discussion of future work are presented in Chapter 6.

Chapter 2

Related Works and Background

This chapter presents necessary background related to the research work presented in this thesis. In Section 2.1, a brief and concise survey of existing related MAC protocols for UWASNs is presented. Section 2.3 provides a brief description of the OMNeT++ simulation environment and MiXiM framework. This description provides the background for the design and development of the simulation environment used to simulate the proposed protocol and to perform comparative performance evaluation with related existing MAC protocols for UWASNs.

2.1 Survey of Existing MAC Protocols for UWASNs

Since energy efficiency is very important for UWASNs, Rodoplu *et al.* proposed an energy efficient MAC protocol (EE-MAC) for highly dense, short range and fully connected UWASNs [46], which introduced a very low duty cycle similar to S-MAC [70] protocol proposed for wireless sensor networks (WSN). The main contribution of EE-MAC was to provide energy efficiency by minimizing the idle listening period. The protocol assumed time invariant propagation delay between any pair of nodes in the network and a large transmission cycle compared to the maximum propagation delay. EE-MAC reduced energy loss due to packet collisions, but throughput of the system was low and cannot accommodate large data dissemination applications. The protocol is designed for specific types

of applications such as asynchronous, delay-tolerant data collection applications that can gather conductivity, temperature and depth (CTD) measurements. Another disadvantage of EE-MAC [46] is that it is not suitable for multi-hop networks because it does not provide any collision avoidance mechanisms for multi-hop networks.

In [58], it was shown that due to the large propagation delay in UWASN, the slotted Aloha (S-ALOHA) performed similarly to pure Aloha with a guard band that was equal to the maximum propagation delay of the network. In [25, 69], ALOHA was studied in multi-hop UWASN for string topology (i.e., chain). In [22], Gao *et al.* introduced a probabilistic model to analyze the ALOHA protocol in UWASN, which is modified and enhanced in order to model and analyze the proposed MAC protocol in this thesis.

Carrier Sense Multiple Access (CSMA), is a widely used protocol in wireless networks and was also studied in UWASN. Syed *et.al* [58] showed that CSMA does not improve the performance of the UWASN due to a large propagation delay compared to a transmission delay since the carrier sensing detects the state of the channel at the transmitter rather than at the receiver. It does not, however, work as an effective means of collision avoidance as in the case of wireless networks.

The slotted floor acquisition multiple access (S-FAMA) protocol for UWASN was proposed in [37], and it extended the FAMA non-persistent carrier sensing (FAMA-NCS) protocol proposed in [23] for terrestrial wireless networks because the terrestrial wireless channel and the UWA channel had relatively large propagation delays. In the original FAMA [21], the channel was acquired by a potential transmitting station prior to any data transmission using RTS (Request to Send) and CTS (Clear to Send) messages as in the collision avoidance technique proposed by the Multiple Access Collision Avoidance for Wireless LAN (MACAW) in [7] after a brief period of carrier sensing. FAMA-NCS enhanced the original FAMA using long RTS and CTS control packets to ensure collision-free data transmission in multi-hop networks with a large propagation delay. S-FAMA eliminated the need for long RTS and longer CTS required in FAMA-NCS by the slotting and synchronizing of frames. This constrained the transmission of both control and data packets

at the beginning of a slot.

The T-Lohi MAC protocol was proposed for UWASN in [55]. It was one of the first MAC protocols to suggest using tones to reserve the channel. Although T-Lohi is as efficient and effective as a MAC, it does not solve hidden station problems. As a result T-Lohi does not perform well in multi-hop networking. Another interesting option made available by T-Lohi was to utilize two receivers (one as a wake-up tone receiver and another as a data receiver) and one transmitter. The advantage of using two different receivers was that this configuration reduced energy consumption during idle listening. The micro-modem proposed by the Woods Hole Oceanographic Institution (WHOI (US)) [20] has a small energy footprint. It has a low power acoustic modem based on Texas Instruments TMS320C5416 DSP and has the capability to be used as a low power tone receiver as well as a data receiver.

Hsu *et.al.* [29] proposed Spatial-Temporal MAC scheduling utilizing the space-time diversity of the underwater acoustic channel. In that protocol, the medium access channel allocation problem had been constructed as a spatial-temporal conflict graph (ST-CG) that was constituted of conflict delays among the transmission links. The graph was then modeled as a new vertex coloring problem. In order to solve the vertex-coloring problem and to find the optimum solution for the scheduling, Hsu *et.al.* proposed a heuristic approach called Traffic-based One-step Trial Approach (TOTA) and a Mixed Integer Linear Programming (MILP) model, respectively. Although this technique had shown better throughput and energy efficiency than existing schemes, it had a number of constraints such as: topology, traffic load, propagation delay on each link in the network, and the interference relationship among the nodes have to be known beforehand.

Similarly, in [34], Kredo utilized the space-time diversity of the underwater acoustic channel in order to share the channel with different nodes simultaneously in time. This approach used node propagation delay estimates to schedule overlapping transmissions without conflicts. It defined a set of schedule constraints based on local topology, traffic patterns and propagation delays among sensor neighbors. It then presented several algo-

rithms, both distributed and centralized, to solve the scheduling problem that was defined as finding an optimum set of transmission time-slots for an individual node that satisfied the schedules constraints. This protocol depended heavily on the given topology, traffic pattern and a good estimation of propagation delay among the neighbors. Another shortcoming is that it is based on a static scheduling technique and thus it is not suitable for on-demand scheduling.

Recently, a number of TDMA-based MAC protocols have been introduced in the literature. In [28], a TDMA-based MAC protocol, named efficient communication scheduling (ECS), utilized continuous time slicing. ECS showed an improvement in channel utilization compared to traditional slotted TDMA in some specific topologies.

In [35], Lee *et. al.* proposed a multi-hop reservation MAC protocol where a single reservation can be used for a multi-hop multiple packet transmission. That protocol provided a better end-to-end delay and throughput for uni-directional data dissemination whereas experienced higher implementation complexities, unfairness and longer reservation time for bi-directional data dissemination.

In [38], Noh *et. al.* proposed a delay aware MAC protocol algorithm in which the propagation delays of the neighboring nodes were locally calculated using the time-stamp information embedded in RTS packets. This enabled the estimation of the expected transmission time for the packet for collision free reception by the receiving node. The algorithm also provided concurrent transmission and reception exploiting temporal and spatial differences among the neighboring nodes.

2.2 UWASN MAC Design Challenges

2.2.1 Underlying Physical Channel Challenges

In wireless radio frequency channels, carrier sensing (CS) has been employed as a successful technique for clear channel assessment (CCA). As the propagation delay of the radio waves

is so small using CCA, a transmitter can detect the status of an ongoing transmission initiated by any node within its interference range. CCA works as an effective collision avoidance technique in a network where each node is within the interference range of other nodes in the network [32, 23, 1, 2].

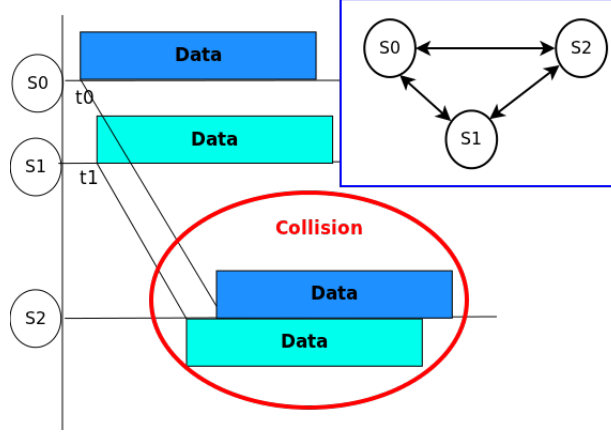


Figure 2.1: Clear Channel Assessment in Acoustic Channel.

Due to the large propagation delay in acoustic channels, CCA cannot detect the status of an ongoing transmission immediately and thus fails to work as an effective collision avoidance technique. As a simple example, as indicated in Fig 2.1 node S_0 and node S_1 both try to send a packet to node S_2 at some point in time. Node S_0 senses the channel and finds it idle and then sends the data packet at time t_0 . Due to a large propagation delay, it arrives at node S_1 at time t_1 . Node S_1 senses the channel before t_1 and finds the channel idle as well. It also transmits the data packet to node S_2 . Both data packets overlap each other at the destination, node S_2 and that causes data collision. Thus, CCA fails to avoid the frame collisions in acoustic channels. In this thesis, the research utilized a short tone instead of carrier sensing to assess the channel. This provided not only the status of the shared media but also an estimation of the number of contending nodes for that shared media.

2.2.2 Topological and Network Intrinsic Challenges

In multi-hop networks, where some nodes are not in the interference range of other nodes, the problem becomes more severe. To avoid data collisions, a transmitting node must know the status of nodes that are two hops away from it. For example, consider a typical multi-hop network scenario as depicted in Figure 2.2. In this scenario, two node sets $s = \{S_0, S_1, S_2\}$ and $h = \{H_0, H_1, H_2\}$ are out of interference range of each other but in the range of $r = \{R\}$. Here s and h are source node sets and r is the receiver. This is a typical network topology mostly seen in the sensor network paradigm wherein data traffic flows from multi-sources to single destination node (Category 1 WSNs) [50].

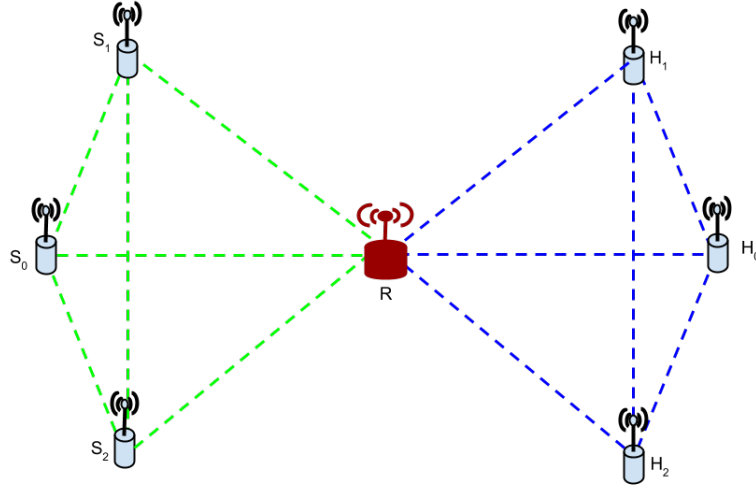


Figure 2.2: Collision domains in wireless network.

Any two nodes $S_i, S_j \in s$ and $H_k, H_l \in h$ where $i \neq j$ and $k \neq l$ are connected to each other by only a single hop. Sets s and h are treated as local collision domains to S_i and H_i , respectively. Nodes in the sets s and h can contend for the channel independently with each other using any channel reservation or contention resolution technique. In a point of time, a single node from each set (assume S_0 from s and H_0 from h) would have won the contention and reserved the channel to send data packet to R . Node S_0 and H_0 do not

have any information concerning the state of the other. Thus, if they send a data packet to R , two data packets arrive at R at the same time and that causes collision. Here, node sets s and h are hidden from each other and form two different independent collision domains. Node sets s and h each considers the other one as a hidden collision domain.

It is evident, therefore, in a multi-hop network that successful collision avoidance depends on two distinct collision domains, i.e., local and hidden collision domains. The MAC protocol design philosophy, presented in this thesis, separates the channel contention resolution into two phases. In the first phase, data packet collisions, caused due to local collision domains, are avoided through local link reservation. This phase is named local-link reservation. In the second phase, data packet collisions, caused due to hidden collision domains, are avoided through controlling the corresponding hidden channels. This phase is named as hidden-link control.

2.3 Overview of Simulation Environment and Protocol Modelling

This research has used OMNET++ [63, 64] as network simulation platform and modify the MiXiM [33, 67] framework to make it suitable for an underwater acoustic sensor network. MiXiM is an OMNeT++ modeling framework created for mobile and fixed wireless networks (wireless sensor networks, body area networks, ad hoc networks and vehicular networks, etc.). It offers detailed models of radio wave propagation, interference estimation, radio transceiver power consumption, and wireless MAC protocols (e.g., Zigbee) [66]. In this section, a description of the background of the simulation environment in respect of simulating the UWASNs and modeling of the MAC protocols and physical layer for the acoustic channel is provided. In sub-section 2.3.1, a concise description of OMNet++ simulation platform is presented and in sub-section 2.3.2 an overview of the MiXiM framework is offered.

2.3.1 Overview of OMNeT++ Simulator

OMNeT++ is a C++-based discrete-event simulator for modeling communication networks, multiprocessors and other distributed or parallel systems. It is a generic simulation engine that can be utilized to simulate any discrete-event system. It is mainly used for network simulation. OMNeT++ is an open-source project, and it can be used either under its own license or under the GNU General Public License (GPL) that also makes the software free for non-profit use [63, 64].

OMNeT++ represents a framework approach. Instead of directly providing simulation components for computer networks, queuing networks or other domains, it provides the basic machinery and tools to write such simulations. Specific application areas are supported by various simulation models and frameworks such as the Mobility Framework or the INET Framework [18]. Therefore, OMNeT++ is not a network simulator alone as it provides a comprehensive framework and integrated development environment to enhance and extend its capabilities. It consists of the following components:

- Simulation Core
- Network Topology Description Language- NED
- Graphical Development Tools
- Generic and Specific Simulation Utilities

Simulation Core

OMNeT++ core is responsible for providing the essential classes to build simple modules and messages that represent not only the message passing among modules but also represents discrete events in the simulation. It also provides a special object called channel that glues two modules as a connection. Each module has two interfaces for communicating with another module called a gate. At the core there is a simulation object that is responsible

for storing all the modules of the environment being simulated including data structures for all of the scheduled events as well as executing the simulation.

Network Topology Description Language-NED

In any OMNet++ simulation environment each building block is treated as a module. Modules can be both simple and compound. A compound module consists of two or more simple modules. In order to define the whole model of a simulation, a network topology description language has been developed called NED. NED is a descriptive language that is used to define a simple module and compound modules as well as a whole network. Recently in NED several object oriented design concepts have been introduced. Inheritance is used to define a sub-module of another module modifying the base module parameters, gates and connections. A model can be defined using the interface of the module instead of the module itself. This provides the possibility of using the same model for different implementations of the module. For example, the module types ConstSpeedMobility and RandomWayPointMobility are needed to enable IMobility to be able to be plugged into a MobileHost module that contains an IMobility sub-module.

NED provides the capability of grouping modules into packages similar to JAVA packages. This eliminates the name clashes between modules. The NED language has an equivalent XML representation, that is, NED files can be converted to XML and back without loss of data, including comments. This lowers the barrier for programmatic manipulation of NED files, as seen, for example, when extracting information, refactoring and transforming NED, generating NED from information stored in other persistence storage systems like SQL databases, and so on. By manipulating the XML, it is possible to change the network topology and behaviour over the fly programmatically.

Graphical Development Tools

The OMNeT++ simulation package comes with an Integrated Development Environment (IDE) that is based on Eclipse [15] which is one of the most popular and widely used open source

IDEs. The IDE provides an easier way to develop new modules and required software components to extend the features of OMNet++. The IDE also contains a graphical editor using NED as its native file format; moreover, the editor can work with arbitrary, even hand written NED code. The editor is a fully two-way tool, i.e., the user can edit the network topology either graphically or in NED source view, and can switch between the two views at any time [64].

Generic and Special Simulation Utilities

OMNet++ provides some essential libraries to perform the following special kind of simulation activities

Real-time Simulation and Network Emulation

The scheduler of the OMNet++ Simulation kernel supports real time scheduling. This scheduling can be used to emulate the network with real time hardware and software systems.

Animation and Tracing Facility

OMNet++ provides animation and tracing facilities of the simulation using *Tkenv*. This allows automatic animation, run time modules and objects inspection.

Statistical Classes

This class libraries for statistical data collection relating to simulations.

Random Number Generator

It provides the facilities to generate different types of random numbers.

Parallel Simulation Support

OMNet++ parallel simulation support contains an MPI (Message Passing Interface)-based library. It enables the creation of large simulations utilizing multiple cores and processors.

Result Analysis Tool

This tool enables users to perform an in-depth analysis of the simulation. It also has the capacity to automate the analysis of the simulation based on pattern matching and rule definitions.

2.3.2 Overview of MiXiM Framework

MiXiM is an open source simulation framework for OMNet++. It is capable of simulating Wireless Sensor Network (WSN) and Mobile Network (MobNet) [66, 33]. The main focus of the MiXiM framework is to design and develop the MAC and PHY layer simulation environment based on OMNet++. In the following two sub-sections, an overview of the design of MAC and PHY layer in MiXiM is elaborated upon.

MiXiM PHY Layer

The MiXiM physical layer is encapsulated into a simple module of OMNet++ called BasePhyLayer. The BasePhyLayer module consists of a number of C++ objects. The details of these objects will be described in Chapter 4. A brief introduction of those modules is given below [14].

Radio: Radio is represented as a state machine in the PHY layer. Any number of states can be modeled by the Radio.

Signal: The underlying physical signal is mapped as a Signal object. It uses a multi-dimensional mathematical mapping that can be used to model any physical signal of any dimension. The Signal is represented as a discrete single or a multi-dimensional value of an arbitrary sampling rate.

Mapping: It represents a mathematical function of an arbitrary domain using arbitrary resolution, although every mapping event must contain the time-dimension of its domain.

AirFrame: It is a container that encapsulates the MAC layer packet and physical layer Signal.

ChannelInfo: It represents itself as a database of all the air frames in the channel for the whole simulation. It also keeps track of the air frames and is used to calculate interference between air frames at receiving nodes.

AnalogueModel: It models the channel effect, such as log shadowing, multi-path, etc. for the channel.

Decider It works as an arbitrator on the receiver side. Its main function is to decide whether a received packet should be dropped or accepted based on some matrices of the receiver such SNIR (Signal to Noise plus Interference Ratio).

MiXiM MAC Layer

Like the BasPhyLayer, the MAC Layer protocol is also encapsulated into the BaseMacLayers simple module. It is noteworthy that each module in MiXiM must be a sub-class of the BaseLayer. The BaseLayer provides basic functionalities for each module in MiXiM. The details of this module are provided in Chapter 4. The BaseMacLayer must implement an interface in order to communicate with the PHY layer. This interface is called MacToPhyInterface [14].

The algorithm of the MAC protocol should be implemented by sub-classing the **BaseMacLayer**. When a packet arrives from the upper layer the BaseMacLayer can create the Signal object based on the transmission power (TX-Power) and bit rate for the transmission. It then encapsulates the upper layer packet into the MacPkt and sends it down to the PHY layer through the MacToPhyInterface interface. For the case of packet reception, the decider arbitrates the packet and sends the packet to the MAC layer through the PhyToMacInterface. There are a few common MAC protocols that are already implemented into MiXiM. For example, ALOHA, CSMA, IEEE 802.11, BMAC, etc.

Chapter 3

Multihop Enabled Energy Efficient MAC (MEEMAC) for UWASN

3.1 Introduction

Sensors deployed underwater operate on batteries. The life of the individual sensor and the whole network depends solely on the energy consumption of these sensors. In underwater acoustic communication, the energy consumption for transmission and reception shows highly asymmetric behavior. Transmission of a packet requires 125 times more energy than its reception [57]. Additionally, due to the large propagation delay in the acoustic channel, a transmitter cannot assess the channel state information (CSI) on the receiver side by any carrier sensing method. Therefore, successful transmission of a data packet may not conclude with successful reception due to packet collisions on the receiver end. Since the energy cost of a transmission is several order of magnitude of a reception, the energy loss due to packet collisions is very high.

For a MAC layer there are mainly five elements that contribute to energy loss in communication. These elements are described briefly below [39, 31, 46, 16, 40, 42, 45, 62, 70].

Collision: The major source of energy loss occurs in a shared wireless medium, when two

or more data or control packets are collided and interfere with one another, and the packets are corrupted causing the energy consumed for the transmissions of these packets to be wasted.

Idle Listening: Here energy is lost due to continued listening on the idle channel when there is no communication to be received.

Over Hearing: When a node receives a packet that is, in fact, destined for another node thereby causing energy is loss due to the packet reception, decoding and processing.

Over Emitting: This type of energy loss occurs when a transmitter sends a packet to the specific node or nodes while the receiving node/nodes are either not ready or are unavailable to receive the packet.

Protocol Overhead: The MAC protocol is designed to allocate the shared medium among the nodes as well as to achieve some related goals. In order to accomplish this some overhead in energy consumption does occur. The major part of this energy consumption is due to exchanging control packets between nodes.

In the proposed protocol the issue of energy loss by utilizing different artifacts and mechanisms has been addressed. The following sections of this thesis will describe: the proposed protocol; its impact and advantages; its efficiencies regarding the energy paradigm; the development of a probabilistic model of the proposed protocol; and quantitative analysis and evaluations of the proposed protocol with existing MAC protocols using the developed probabilistic model.

In the proposed protocol, a successful data transmission implies that the data has been successfully received by the intended receiver or receivers. A successful data transmission and reception is visualized by a logical time frame of variable length that consists of three distinct parts of the MEEMAC protocol depicted in Fig. 3.1. It is referred to as a protocol frame.

1. Local-link reservation.

2. Hidden-link control.
3. Data transmission.

MEEMAC is a random access, contention-based distributed MAC protocol. However, it reserves the channel prior to any data transmission. In MEEMAC, a single protocol frame is an aggregation of a number of equal length time slots. Each with a local-link reservation, hidden-link control and data transmission consisting of one or more time slots. While a node is contending with other nodes for reserving the channel, each of these has a time slot called a contention round (CR). The time duration of the slot is determined by the maximum range of the transmitters used in the network. In order to make sure that each node in the transmission range should be aware of the state of the transmitting node the slot duration must be greater than maximum propagation delay of the network plus the transmission delay of the longest control packet [23, 37, 55].

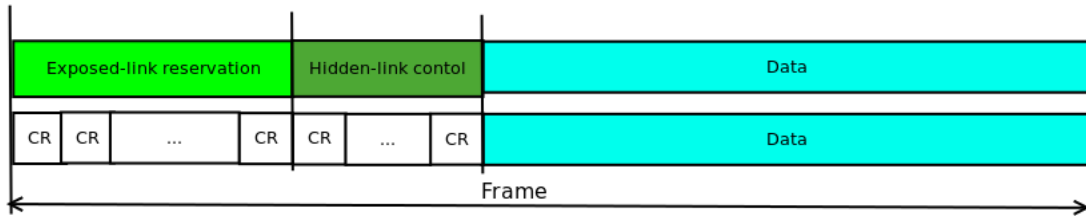


Figure 3.1: Successful data transmission frame structure for the proposed protocol.

Local Link Reservation

In the local-link reservation phase, short tones are used to resolve the contention among the nodes. When the MAC layer receives a packet from the upper layer, EEMAC protocol queues it and starts the local-link reservation. At the beginning of a slot in the protocol frame, the node initiates contention to reserve the local link by transmitting a tone. The contending node switches its radio to the listening mode as soon as the transmission of the tone ends and it then starts listening to the channel until the current slot duration expires. This completes a single contention round. During this period, if the contending node does

not receive any other tones or packets (either control or data), the contending node infers that there is no other node in contention for the link. This concludes a successful local-link reservation and the winning node is going to initiate next phase the hidden-link control phase.

The reception of at least one tone in a CR indicates that there are other nodes that also want to transmit. In this case the contending node increases its counter by the number of received tones and, at the beginning of the next slot it goes to a back-off state. The random back-off period is equal to the number of slots that are uniformly distributed between zero and the number of contending nodes. When the back-off timer expires, the node resumes the contention and this process continues until it can successfully reserve the local link. A single successful local-link reservation phase consists of one or more CRs. This whole time duration is called a reservation period (RP). A node usually traverses through a number of states in order to complete an RP. A detailed description of the state model of the MEEMAC protocol is described in a later section of this chapter.

Hidden Link Control

In order to eliminate collisions due to hidden collision domains, local-link reservation is supported by the hidden-link control phase. Hidden-link control is carried out by the exchange of two distinct control packets prior to a data transmission. These additional control packets ensure that the nodes connected to the destination by hidden links defer their transmissions while the destination is receiving the data packet from its local link. The additional control packets are called request to send (RTS), and clear to send (CTS). The use of RTS and CTS exchanges was first described for Split-Channel Reservation Multiple Access (SRMA) protocol in [60], although the name of the control packets were different- *Request Packet* and *Answer to Request Packet*, respectively. In SRMA two different channels are used for exchanging these two packets, but in the MEEMAC same channel is used to exchange of these control packets.

The winning node of the local-link reservation initiates the hidden-link control phase by

broadcasting RTS and waits for one more slot to receive the CTS from the intended receiver. If the sender successfully receives CTS from the receiver, it infers that the control link reservation was successful. On the onset of the next slot the sender sends the data packet. If the sender does not receive the CTS from the receiver within the next slot duration, it goes to the back-off state. Each node in the local collision domain receives the RTS packet and switches its state to sleep mode. Correspondingly, each node in hidden collision domain receives CTS and switches its state to sleep mode. As in local-link reservation, a node usually cycles through a number of states in order to complete a successful hidden-link reservation. A detailed description of the state model of the MEEMAC protocol is described in a later section of this chapter.

Due to a large propagation delay of the acoustic channel, with respect to transmission delay of the control packets, there is a possibility that more than one complete RTS packet is successfully received by an intended receiver in a single time slot [37]. This raises a novel issue of prioritizing the responses of the RTS packets. In the MEEMAC, as a simple solution, we assign the priority based on the reception time of the RTS packet. The priority is set the highest for the RTS that has been received lately. This implies that if multiple RTSs are received by the intended receiver, the CTS will be sent for the RTS that took the longest time to reach to the receiver. This provides a spatial fairness to the remote node.

3.2 Example Scenario Explained

A typical successful data transmission scenario which is represented by a logical time frame, is depicted in Fig. 3.2 for a typical network scenario shown in Fig. 2.2. It is assumed that each node of the collision domain wants to send the data packet to node R , the receiving node. At the beginning of a frame (i^{th} slot), nodes S_0 , S_1 and S_2 of the collision domain s , and nodes H_0 , H_1 and H_2 of the collision domain h start a contention for local-link reservation by transmitting tones. After transmission of the tone, each contending node switches to listening mode to detect the tones from neighbors. By the end of the slot, S_0 ,

S_1 and S_2 nodes would have recorded the number of contending nodes (N_{nc}), of which there are three in this scenario. Similar action flow occurs with nodes H_0 , H_1 and H_2 . At this instant of time, since each contending node from both collision domains experiences more than one contender, each node switches its state to the back-off mode and the duration of the back-off mode is equal to a random variable uniformly distributed on the interval $[0, N_{nc})$ slots. This scenario assumes that nodes S_0 , S_1 , H_0 and H_2 select the zero back-off slot, and S_2 and H_1 select back-off slots 1 and 2, respectively. Therefore, S_0 , S_1 , H_0 and H_2 send another tone at the beginning of the $(i + 1)^{th}$ slot, while S_2 and H_1 are both in the back-off slot. By the end of the slot, each contending node has found that the number of contending nodes is now two. Like the previous slot, now the contending nodes go to the back-off mode by selecting a uniformly distributed random number between $[0, 2)$ slots. This assumes that nodes S_0 and H_0 select zero back-off slots and others receive non-zero back-off slots. Nodes S_0 and H_0 send another tone at the beginning of the $(i + 2)^{th}$ slot and start listening for the tones for rest of the slot. By the end of this slot, contending nodes (S_0 and H_0) do not receive any tone and thus they decide that they have reserved the local link.

Nodes S_0 and H_0 have reserved the corresponding local link simultaneously at the $(i + 2)^{th}$ slot; both nodes send RTS control packets instead of data packets at the beginning of the $(i + 3)^{th}$ slot. The destination node R receives both control packets successfully due to slight delays caused by the space-time uncertainty of the acoustic channel. The destination node R prioritizes the control packets based on their arrival time and gives higher priority to the packet that arrives the latest. It then broadcasts a CTS packet at the beginning of the $(i + 4)^{th}$ slot that allows S_0 to transmit in the next slot and prohibits H_0 to transmit. All other nodes of the domain h keep themselves in a *sleep* mode, while the transmission of the data packet continues from node S_0 to node R . Thus, by incorporating two phase reservation mechanisms, data packet collisions are avoided in multi-hop networks.

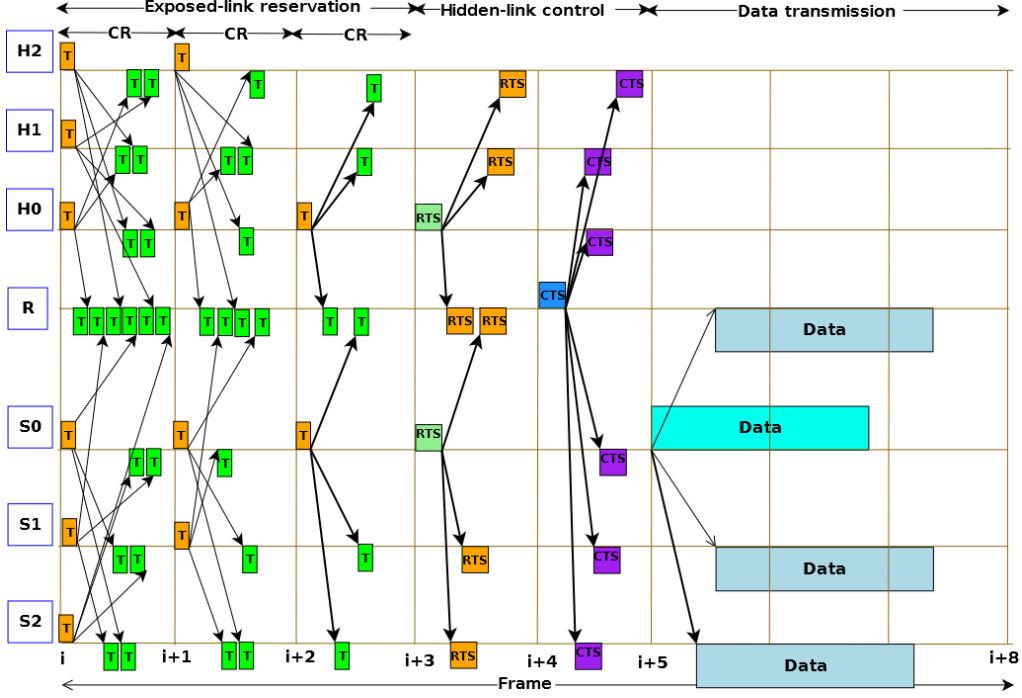


Figure 3.2: Medium access control (MAC) mechanism of the proposed protocol.

3.3 Collisions Avoidance Explained

In this section, it is going to be described that in the absence of hidden-link control, data packets are bound to collide and the successful local-link reservation does not guarantee successful reception of the packet by the receiver. For this discussion the same network configuration as shown in Fig. 2.2 will be considered. The local-link reservation and data transmission phase for the scenario is shown in Fig. 3.3. As described earlier, nodes in collision domains s and h , start corresponding local-link reservation in the beginning of a new frame. At the end of the $(i + 2)^{th}$ slot, nodes S_0 and H_0 have reserved the corresponding local link and start data transmission at the beginning of the $(i + 3)^{th}$. Both nodes successfully transmit the data packet but the data packets are collided at the receiver and the receiver could not decode the data packets correctly. Eventually, both the data packets are lost and they need to be re-transmitted. This collision does not only result in data packet loss but also results in the loss of several valuable resources. Since

the energy requirements for data transmission is several order of magnitude more than for data reception, the transmitting nodes lose a significant amount of energy. Additionally, data loss must be compensated for by the retransmission of messages from the upper layer, which consequently causes more energy loss and incurs more delays.

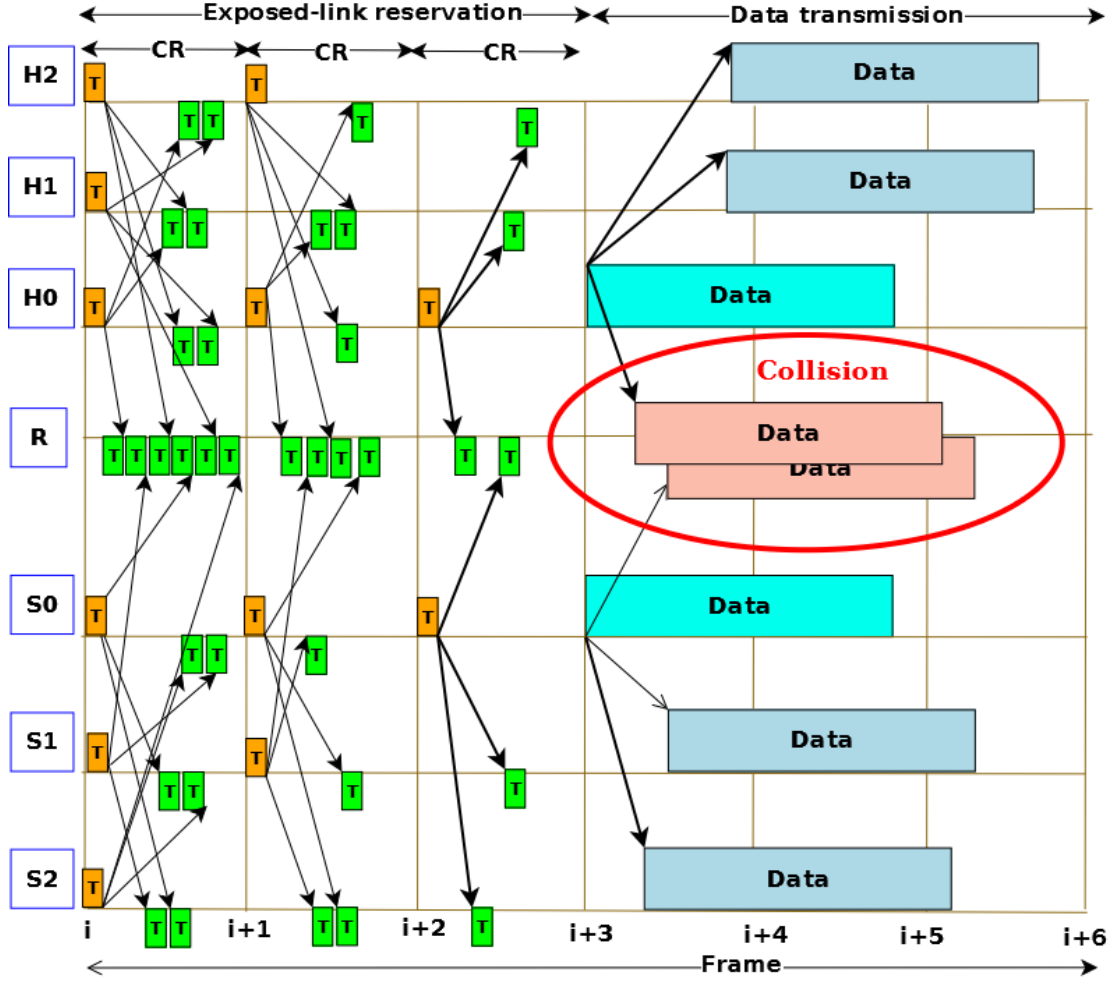


Figure 3.3: MAC without hidden-link control.

3.4 Energy Conservation Strategies

As described in Section 2.2.1, the carrier sensing is ineffective in the acoustic channel to predict the state of other nodes in local domain, thus a short duration tone is utilized to

resolve contention among the nodes. This is as an active way to inform other nodes of the intention of the transmitting node. In order to reduce the energy loss due to *Idle listening*, the MEEMAC protocol will utilize an acoustic modem that consists of two receivers and one transmitter. One of the receivers works as wake-up tone receiver that operates on very low power mode consuming about $500\mu W$; another one works as a data receiver that consumes approximately $20mW$. The data receiver is kept in sleeping mode most of the time and is turned on by the wake-up tone receiver when needed [68, 20].

Collision is the major cause of energy loss in UWASN. The major objective of MEEMAC is to avoid collision among the different types of packets by reserving the channel prior to data transmission. Two phase reservations add extra benefits in this regard. In the local-link reservation phase, the contending nodes in the local domain are eliminated from contention using tones. This eliminates costly exchanges and collisions among the control packets if used instead of tones. Furthermore, the number of nodes contending in the hidden-link control phase is reduced due to the elimination of nodes in previous phase. This results in fewer numbers of control packets required to reserve the hidden-link control. As a result, overall protocol-overhead is reduced and corresponding energy loss is mitigated.

Overhearing of the data packet is eliminated by switching the node to *Sleep* state whenever data is expected to be received that is not intended for the node. This mechanism is described in-depth in Section 3.5. Over emitting is absent in the MEEMAC since a channel must be reserved and CTS must be received from the intended receiver prior to sending the packet to the receiver.

3.5 MEEMAC State Transition Model

A node traverse through several states is required in order to reserve the channel to transmit a data packet. In Fig. 3.4, the MEEMAC state diagram is depicted. There are three main types of events that cause a node to change its state.

- i) Transmission Completion: This encompasses any type of transmission: Tone, RTS,

CTS and Data transmission. The events are symbolized as E_{tx}^t , E_{tx}^{rts} , E_{tx}^{cts} and E_{tx}^{data} for Tone, RTS, CTS and Data, respectively.

- ii) Reception Completion: Similarly events E_{rx}^t , E_{rx}^{rts} , E_{rx}^{cts} and E_{rx}^{data} refer to the end of receptions of Tone, RTS, CTS and Data, respectively. However, E_{rx}^{xrts} , E_{rx}^{xcts} and E_{rx}^{xdata} represent the reception of packets that are intended for another node.
- iii) Timeout: This includes different types of time out expiration events, such as, current slot expire (E_{se}), back-off time expires (E_{bse}), sleeping time expires (E_{sse}), wait time for expires (E_{cse}) and wait time for Data expires (E_{dse}).

The following is a description of each of the states in which a node is attained in the MEEMAC protocol.

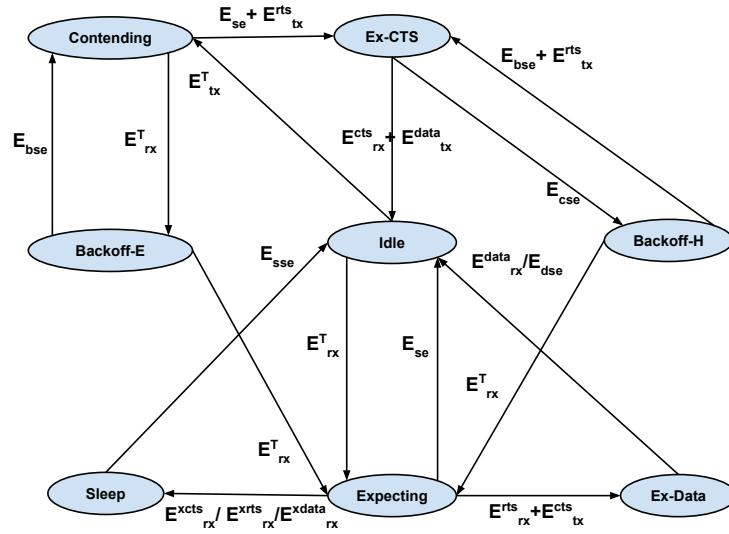


Figure 3.4: State diagram of MEEMAC protocol.

Idle: A node remains in *Idle* state when it has intention to send or receive. In this state, the radio keeps listening to the acoustic channel, thus wasting the energy due to idle listening. The strategy adopted to minimize this energy loss is described in Section 3.4. When a data packet is queued from the upper layer (i.e., Network Layer), the node

initiates a contention and switches to *Contending* state or when any tone is received the state is switched to *Expecting* state.

Contending: A node stays in this state while contending in the local-link reservation phase. If in this state a node receives one more tone, it switches to *Backoff-E* state. If no tone is received in this state (i.e., event, E_{se} is fired), the node wins the local-link reservation, it then sends the RTS and switches its mode to *Ex-CTS* (Expecting for CTS) state.

Backoff-E: A simple back-off algorithm, mentioned in Section 3.1, is adopted to calculate the number of slots it should retain in this state. When the event, E_{bse} is fired, it goes back to *Contending*. While it is in *Backoff-E*, if any tone is received, it switches to *Expecting* state.

Expecting: This is the state where a node is expecting a packet to be received within a current time slot. When a node is in *Expecting* state, it wakes up the radio of the data receiver so that either the control or data packet can be received. No packet will be received until the node has passed through this state. While a node is in this state, if it receives one or more RTS intended for itself, *i)* first, it prioritizes the response based on the strategy mentioned in Section 3.1, *ii)* secondly, it then sends CTS to the chosen sender, and *iii)* thirdly, it switches its mode to *Ex-Data* (Expecting for Data) state. If the node receives RTS, CTS or a Data packet intended for another node (i.e., event E_{rx}^{xcts} , E_{rx}^{xrts} or E_{rx}^{xdata} is fired), it goes to *Sleep* state and thus conserves energy.

Ex-CTS: This represents the state where the node has already sent an RTS and is waiting for the corresponding CTS. If the node successfully receives the CTS before the time out for CTS (i.e., Event E_{cse}), the node infers that the hidden-link reservation is successful. Then the node sends the data packet to the receiver. After the completion of the data transmission (i.e., Event E_{tx}^{data}), the node switches to *Idle* state.

Ex-DATA: Here a node has already sent a CTS and is now waiting for data packet. If the node receives either the data packet successfully (i.e., Event E_{rx}^{data}) or the wait time for data packet (i.e., Event E_{dse}) expires, it then switches to the *Idle* state.

Backoff-H: This back-off state indicates that a node has already sent a RTS and its wait time for CTS has expired. Similarly a back-off algorithm, mentioned in Section 3.1, is adopted to calculate the back-off time out.

Sleep: In this state, a node is incapable of either transmitting or receiving; both of the receivers, wake up and data receivers, are kept off. The time out of sleep duration is calculated based on the type of packets the node received in *Expecting* state. If the event E_{rx}^{xcts} has occurred, the sleep duration would be the equivalent time slot of the transmission delay (S_{tdata}) of the data packet. For the event E_{rx}^{xrts} and E_{rx}^{xdata} , the sleep duration would be $S_{tdata} + 1$ and $S_{tdata} - 1$, respectively.

3.6 Modelling MEEMAC Protocol

In this section, the channel utilization, end-to-end delay and energy consumption for the proposed protocol are calculated and its performance with the T-Lohi protocol by modelling the protocols in a typical sensor network scenario are evaluated.

3.6.1 Channel Utilization

In order to analyze the performances of the proposed protocol for a multi-hop network with hidden collision domains, the network topology utilized by Tobagi and Kleinrock [32] is assumed. The analysis is based on the following assumptions:

1. The network consists of a set of source nodes and a single receiving node. Each node is hidden from the rest of the nodes but is connected with the receiving node. It is assumed that there are $N + 1$ nodes including the receiving node. In this set-up, each

source node experience $N - 1$ has hidden nodes. Each source node with receiving node forms a collision domain.

2. The packet arrival rate to the MAC layer is assumed to have a Poisson distribution with a mean arrival rate of λ packets/seconds.
3. Each data packet has a constant transmission duration of T_d seconds.
4. Each node acts as a source and the receiving node acts as a sink.

The channel utilization, C_u of the network, as defined in [32], is given by

$$C_u = \frac{\bar{U}}{\bar{B} + \bar{I}}, \quad (3.1)$$

where \bar{U} represents the expected time duration that the receiving node spent for receiving the payload without collision, \bar{I} represents the expected duration of the idle period, and \bar{B} represents the expected duration of the busy period with or without collisions. At the receiving node, a collision could occur when a data packet collides either with other data packets or with tones. With respect to the timeline of the receiving node, the expected vulnerability period for a data packet collision is equal to T_d , which is the transmission duration of the data packet. This case holds when all nodes are synchronized and they will transmit only at the beginning of a slot. A typical data packet collision can be visualized by Fig. 3.5. After any successful local-link reservation, the data packet transmission can be modelled as Slotted ALOHA (S-ALOHA) with non-negligible propagation delay [3, 25, 69, 24]. The expected vulnerability period for a packet will be T_d for S-Aloha in an acoustic channel. Therefore, the probability of successful data transmission, P_{sd} is given by

$$P_{sd} = e^{-T_d \lambda (N-1)}. \quad (3.2)$$

The total busy period can be divided into three parts:

- Busy due to successful data transmission, T_{bs} .

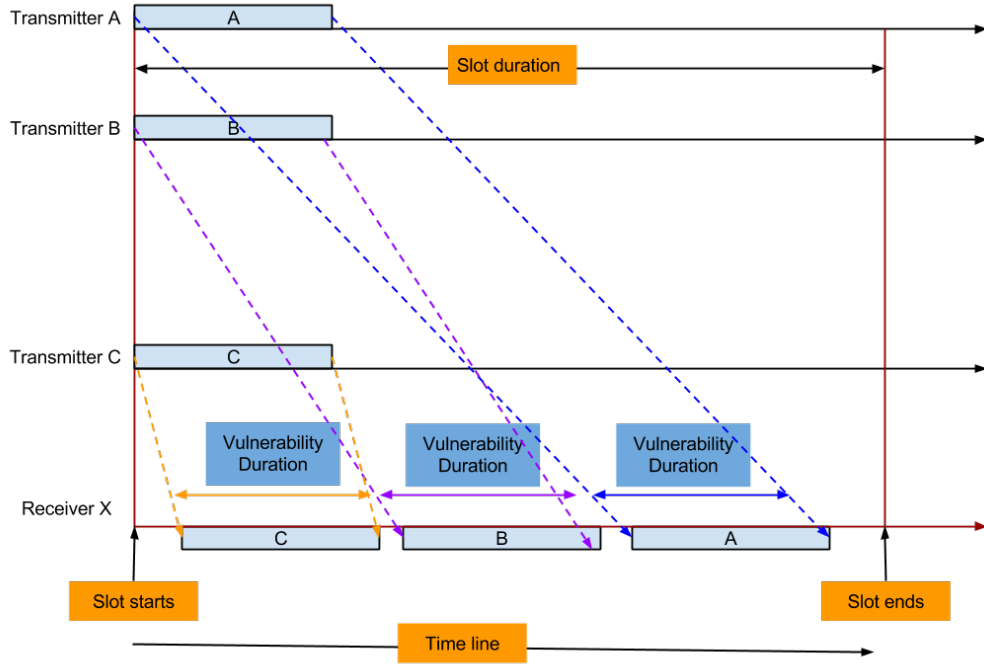


Figure 3.5: Expected vulnerability period

- Busy due to collisions of data packets at the receiver, T_{bc} .
- Time spent in local-link reservation, R_{el} .

The successful busy time is equal to the data transmission duration, $T_{bs} = T_d$. The busy time due to collisions is $T_{bc} = T_d + \tau_{max}$, where τ_{max} represents the maximum propagation time for any packet in the network. The expected number of contention round (CR) required for a successful local-link reservation, as calculated in [56], is given by

$$N_{CR} = \sum_{j=1}^{N_{cd}} P_{N_{cd},j} (E[X_{N_{cd}}] + T_j), \quad (3.3)$$

where N_{cd} is the number of nodes of a collision domain in which nodes are connected with one another by local links. In this analysis, $N_{cd} = 2$, since only one source is connected to the sink. In (3.3), $E[X_{N_{cd}}]$ represents the expected length of a super round with N_{cd}

number of nodes [56]. A super round consists of one or more contention rounds. A super round starts when one or more nodes start to contend in the current slot and it ends when one or more nodes try to contend in any other future slot. The quantity, $P_{N_{cd},j}$ represents the transition probability of the Markov chain used to model the channel reservation and T_j represents the expected time of channel reservation of any node where the number of nodes in the network is j [56]. The mean idle time is the time the sink node is not receiving any packets and is given by $\bar{I} = \frac{1}{N\lambda}$ and the mean useful data utilization time, \bar{U} is given by $\bar{U} = P_{sd}T_d\alpha$, where $\alpha = \frac{Pay\ Load\ Length}{Data\ Packet\ Length}$. The local-link reservation period calculated in (3.3) is also affected by hidden collision domains. It is assumed that the local-link reservation period of each collision domain is independent of each other and is uniformly distributed with the probability $\frac{1}{N-1}$, where $N - 1$ represents the number of collision domains. A single contention round is equal to the slot duration, $T_{sl} = T_t + \tau_{max}$. Hence, the effective local-link reservation period is given by

$$R_{el} = N_{CR}(N - 1)T_{sl} \quad (3.4)$$

Since the T-Lohi protocol has a similar channel reservation as the local-link reservation, the channel utilization for the T-Lohi protocol is given by

$$C_u = \frac{P_{sd}T_d\alpha}{P_{sd}T_{bs} + (1 - P_{sd})T_{bc} + R_{el} + \frac{1}{N\lambda}} \quad (3.5)$$

In MEEMAC protocol, the slot duration is increased to $T_{sl,p} = \tau_{max} + max(T_{NP})$, where T_{NP} represents the transmission duration of the notification packets. After a successful local-link reservation, the sender and the receiver exchange notification packets (RTS/CTS) to control the hidden links. The time duration of this exchange is $2T_{sl,p}$. If the destination node successfully receives one or more RTS packets, it sends an CTS packet that is then successfully delivered to the sender in the next slot. The effective vulnerability duration for exchanging notification packets is $T_{CTS} + T_{RTS}$ where T_{CTS} and T_{RTS} represent duration of the CTS and RTS packet, respectively.

Hence the probability of the successful data transmission for the proposed protocol is calculated as follows

$$P_{sd,p} = e^{-(T_{CTS}+T_{RTS})\lambda\beta(N-1)}. \quad (3.6)$$

In (3.6), β refers to the coefficient of channel access rate to start the contention for hidden-link reservation phase. Prior to the point of saturation of the network the value of β remains 1, but when the network reaches the saturation β follows the equation, $\beta = \frac{\lambda_{th}}{\lambda}$, where λ_{th} is the packet arrival rate in the point of saturation. The time required for successful data transmission is $T_{bs,p} = 2T_{sl,p} + T_d + \tau_{max}$ and the time spent for the failed transmission or collision is $T_{bc,p} = 2T_{sl,p}$ [37]. The expected time required for the local-link reservation is given by ([25])

$$R_{el,p} = N_{CR}(N-1)T_{sl,p} \quad (3.7)$$

The mean idle time is $\bar{I} = \frac{1}{N\lambda\beta}$ and the mean useful data utilization time is $\bar{U} = P_{sd,p}T_d\alpha$. Therefore the channel utilization for the proposed protocol is given by ([32])

$$C_u = \frac{P_{sd,p}T_d\alpha}{P_{sd,p}T_{bs,p} + (1 - P_{sd,p})T_{bc,p} + R_{el,p} + \frac{1}{N\lambda\beta}}. \quad (3.8)$$

3.6.2 End-to-end Delay

Previously, this research calculated the probability that a data packet successfully delivered to the receiver without any collision. Here, it is assumed that each transmission cycle (local-link reservation, hidden-link control and data transmission) event is independent with respect to one another. Therefore, the event of successful transmission preceded by zero or more unsuccessful transmission events can be modeled as a random variable of type geometric distribution [32]. For the T-Lohi protocol, the expected number of transmissions required for a single successful data packet reception by a receiver is given by

$$\begin{aligned} Q &= \sum_{i=0}^{\infty} (1 - P_{sd})^i P_{sd} \\ &= \frac{1 - P_{sd}}{P_{sd}} \end{aligned} \quad (3.9)$$

Similarly, for the proposed protocol, an expected number of transmissions required for a single successful data packet reception by a receiver is given by

$$\begin{aligned} Q_p &= \sum_{i=0}^{\infty} (1 - P_{sd,p})^i P_{sd,p} \\ &= \frac{1 - P_{sd,p}}{P_{sd,p}} \end{aligned} \quad (3.10)$$

where $P_{sd,p}$ and P_{sd} are the probabilities of successful transmission for the proposed protocol and the T-Lohi protocol, respectively. In case of the T-Lohi protocol, the total time of data transmission and propagation is $T_d + \tau_{max}$ plus the local-link reservation time, R_{el} . The end-to-end delay is given by

$$D = Q(T_d + \tau_{max} + R_{el}) + T_d + \tau_{max} + R_{el} \quad (3.11)$$

Similarly, the delay for the proposed protocol is given by

$$D_p = Q_p(2T_{sl,p} + R_{el,p}) + T_d + \tau_{max} + 2T_{sl,p} + R_{el,p} \quad (3.12)$$

3.6.3 Energy Consumption

Assume that maximum transmission power is given by W for tone, control and data packets. In the case of the T-Lohi protocol, energy loss due to data collision for a single successful data packet transmission is given by

$$E_{dc} = QT_d W \quad (3.13)$$

Energy is also wasted for those channel reservations that ended with data collisions. So the energy loss due to the failed reservation period is given by

$$E_{fr} = Q\left(\frac{R_{el}}{T_{sl}}\right)T_t W \quad (3.14)$$

Energy required for a successful reservation period, E_{sr} and data transmission, E_s are, respectively, given by

$$E_{sr} = \left(\frac{R_{el}}{T_{sl}}\right)T_t W \quad (3.15)$$

and

$$E_s = T_d W \quad (3.16)$$

Hence, total energy overhead or loss for a single successful data packet transmission for the T-Lohi protocol is given by

$$E_l = E_{dc} + E_{fr} + E_{sr} \quad (3.17)$$

In case of the proposed protocol, energy is lost due to notification packets collisions and failed local-link reservations. Energy loss due to notification packets collisions is given by

$$E_{npc} = Q_p(T_{CTS} + T_{RTS})W, \quad (3.18)$$

while energy loss due to failed local-link reservation is given by

$$E_{fr,p} = Q\left(\frac{R_{el,p}}{T_{sl,p}}\right)T_t W \quad (3.19)$$

Energy required for a successful local-link reservation, $E_{sr,p}$ hidden-link control, E_{nps} and data packet transmission, $E_{s,p}$ are respectively given by

$$E_{sr,p} = \left(\frac{R_{el,p}}{T_{sl,p}}\right)T_t W, \quad (3.20)$$

$$E_{nps} = (T_{CTS} + T_{RTS})W, \quad (3.21)$$

and

$$E_{s,p} = T_d W. \quad (3.22)$$

Hence, total energy overhead or loss for a single successful data packet transmission for the proposed protocol is given by

$$E_{l,p} = E_{npc} + E_{fr,p} + E_{sr,p} + E_{nps} \quad (3.23)$$

3.7 Quantitative Evaluation

The performances of the proposed protocol and the T-Lohi protocol are evaluated to demonstrate how hidden collision domain and traffic loads can affect the channel utilization,

the end-to-end delay and energy overhead. The same parameters as used in [55] are utilized to fairly compare the results. Table 3.1 provides the values of protocol parameters used in both quantitative analysis and simulation. Bit-rate of the acoustic modems (wake-up tone and data receiver) and power consumptions parameters are listed in Table 3.2.

Parameters	Length(in bytes)
Payload	625
App Header	5
Netw Header	5
Mac Header	5
Phy Header	5
Tone	5
CTS	10
RTS	10

Table 3.1: Protocol parameters.

Fig. 3.6 demonstrates the effects of hidden nodes and the packet arrival rate on the overall channel utilization of the network. The proposed protocol outperforms the T-Lohi protocol for all network configurations (networks of 1, 3 and 5 hidden nodes). At a higher load, when the network saturates, the difference between channel utilizations of

Bit-rate: 8000 bps		
Mode	Data	Wake-up Tone
Transmit(max)	2W	2W
Receive	20mW	0.5mW
Idle/Listen	20mW	0.5mW

Table 3.2: Acoustic modem parameters.

the two protocols widens significantly. It is observed that the channel utilization of the T-Lohi protocol drops radically even at low loads when the number of hidden nodes is high. However, the channel utilization of the proposed protocol is stable and mostly outperforms that of the T-Lohi protocol. As an example, for the network configuration having three hidden nodes, the channel utilizations of the T-Lohi and MEEMAC protocol are 0.004 and 0.19, respectively, when the traffic rate is 2.0 packets per second. This shows the impact of hidden nodes in the T-Lohi protocol, which causes a drastic decrease in channel utilization. The channel utilization of the T-Lohi protocol under high traffic loads is low and it gets worse with an increasing number of hidden nodes, while the proposed protocol provides stable and better channel utilization under the same conditions. The proposed

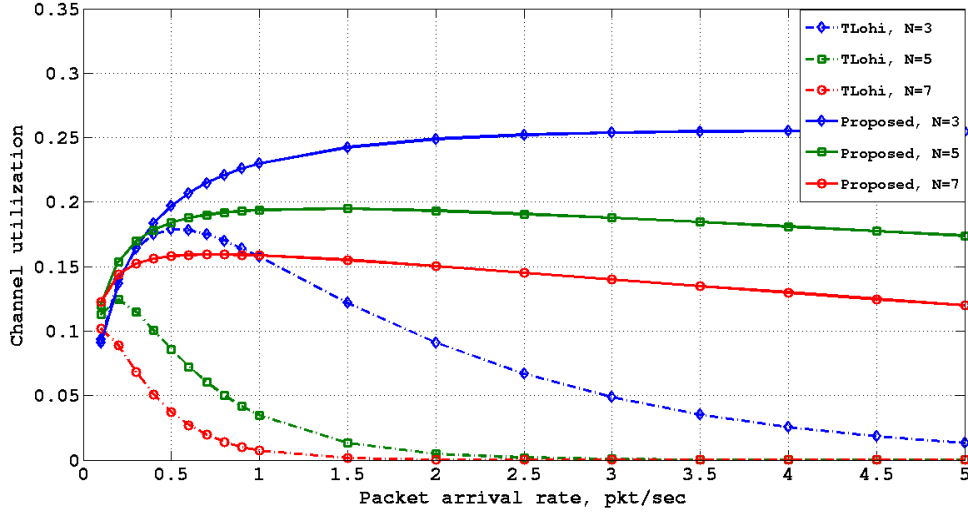


Figure 3.6: Channel utilization vs. packet arrival rate.

protocol achieves lower and stable end-to-end delays than the T-Lohi protocol as shown in Fig. 3.7. As the number of hidden nodes and packet arrival rates increase, the end-to-end delay of the T-Lohi protocol increases by several order of magnitudes whereas the proposed protocol achieves constant end-to-end delays. For the sake of illustrating this condition, for the network configuration having three hidden nodes, end-to-end delays for the proposed protocol are 3.32 and 3.78 seconds for packet arrival rate of two and five packets per second,

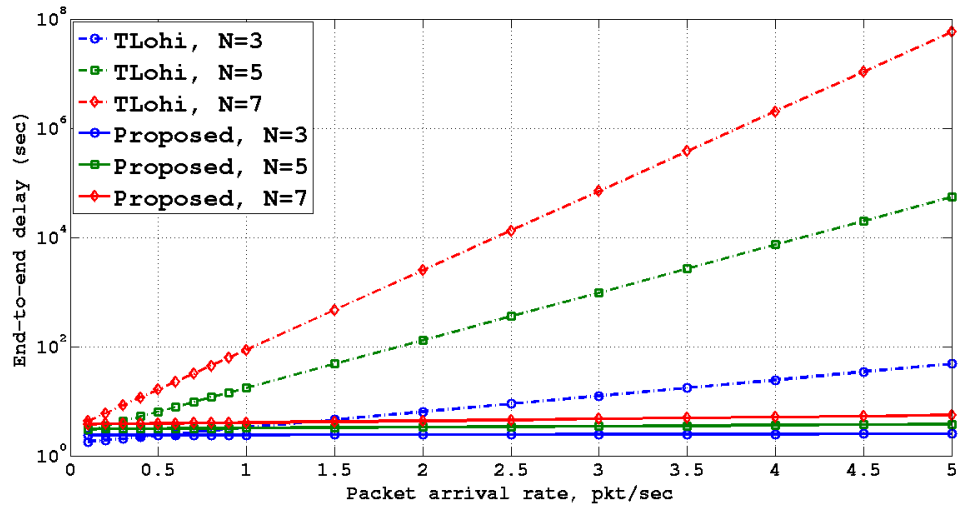


Figure 3.7: End-to-end delay vs. packet arrival rate.

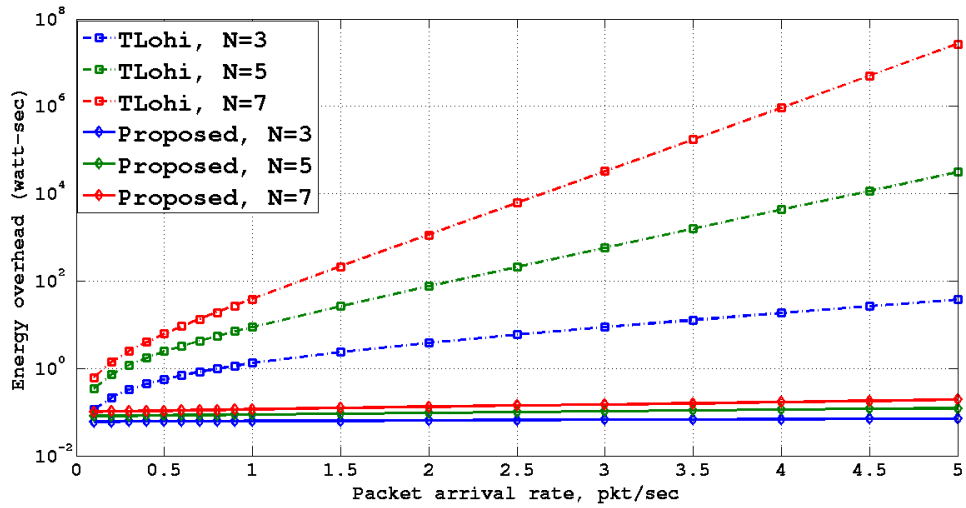


Figure 3.8: Energy overhead vs. packet arrival rate.

respectively. But in the same condition, end-to-end delays for the T-Lohi protocol are so long that they are not acceptable for a viable network. This improvement is achieved by eliminating the data packet collisions caused by hidden nodes.

In Fig. 3.8, we have compared the total energy loss/overhead for per single successful data packet transmission for both the T-Lohi protocol and the proposed protocol. From the performance graph, it is evident that the proposed protocol outperforms the T-Lohi protocol irrespective of any traffic load and number of hidden nodes in the network. Moreover, the proposed protocol shows stable and constant energy overhead in the saturation region whereas the energy overhead of the T-Lohi protocol increases indiscriminately.

Chapter 4

Simulation Design for UWASN MAC and PHY Layer

4.1 Introduction

Though there are many commercial and academic research based acoustic modems available for underwater communications, yet most of the time, it is not feasible to implement newly designed network protocols in those modems and investigate the performance of the protocol in real world scenario. The cost associated with implementation, deployment and investigation of the protocol is usually very high and the time required for this is also very long. Therefore network simulations are largely used to investigate the performance of the network protocols. Simulation not only provides cost effective solution for designing, debugging and validating the network protocol but also reduces the time of development. In addition, the complex network topologies are not possible to be modeled analytically, network simulation is the only option to study and evaluate the newly developed network protocols.

There are a number of network simulators available to simulate the WSNs - some of them are commercially available and some are based on open source concept. OPNeT [11] is an example of commercially available network simulator which is a very popular one among professional communities. There are many network simulators available in academic

domains such as NS2 [36], OMNeT++ with MiXiM [63, 14], Ptolemy with Visualsense [9, 6], JavaSim [61], GloMoSim [5], NS3 [27], etc. There is no network simulator available to simulate UWASNs. MiXiM is one of most popular open source simulation framework for OMNet++. It is capable to simulate Wireless Sensor Network (WSN) and Mobile Network (MobNet) [66, 33]. The main focus of MiXiM framework is to design and develop MAC and PHY layer simulation environment based on OMNet++. In this chapter, the design of a new simulation environment tailoring MiXiM framework is discussed , in order to perform network simulation for UWASNs.

4.2 MixiM Architectural Overview

As mentioned earlier, MiXiM framework utilizes the concept of OMNet++ that is based on purely Object Oriented Programming (OOP). Each component in MiXiM framework is an object. In MiXiM, a typical simulation network, depicted in Fig 4.1, mainly consists of three main components: *a) BaseWorldUtility*, *b) Nodes*, and *c) ConnectionManager* [33, 67]. In following subsections, these components are described in details.

4.2.1 Base World Utility

The module *BaseWorldUtility* models the physical area of the simulation as a *playGround* object which can be either two and three dimensional area. *BaseWorldUtility* also provides the mean to model the *playGround* as a surface of a torus. *BaseWorldUtility* also exposes utility and information methods for the whole simulation. One of the most important parameters of the *BaseWorldUtility* is *speedOfLight* which is required to determine the propagation delay when radio wave is used as a carrier. Therefore, in order to simulate UWASNs using sound wave, it is necessary to extend the *BaseWorldUtility* to incorporate essential changes.

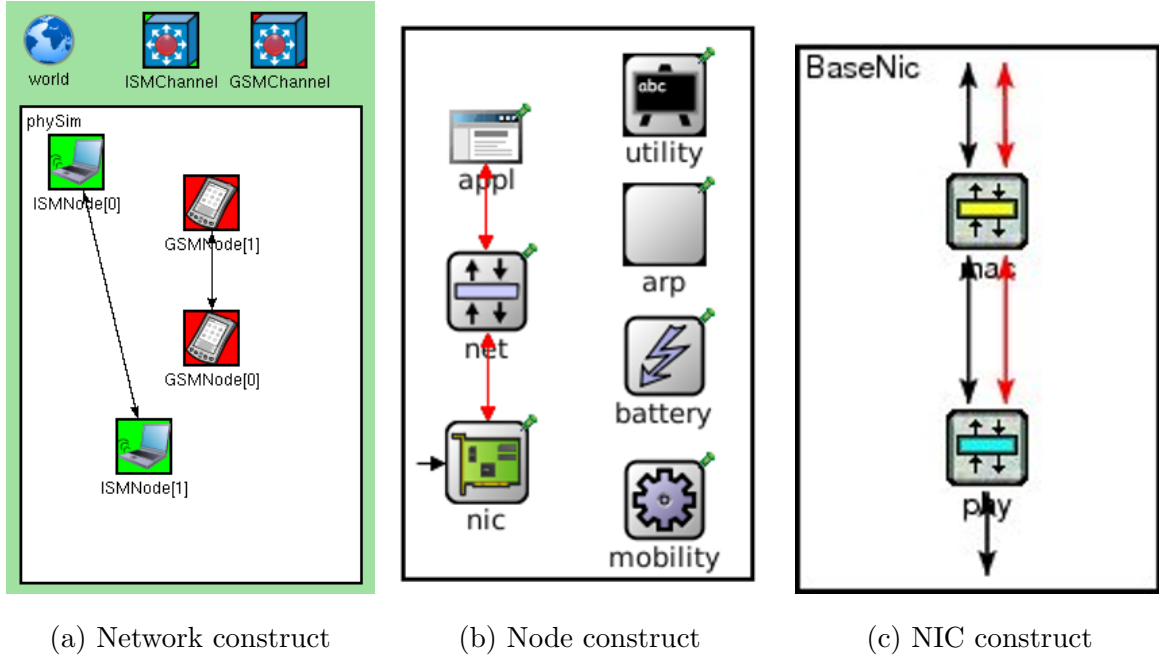


Figure 4.1: Network simulation constructs [33, 67]

4.2.2 Nodes

In MiXiM, *node* module represents any device with capable of networking, such as a sensor node, personal computer, or a server. A single *node* depicted in Fig 4.1b consists of application (*appl*), network (*net*) and NIC (Network interface card) modules that resemble the corresponding layers of OSI model [71]. NIC is a combination of MAC and PHY layer shown as a group, since these two are usually tightly coupled and designed differently for different communications technologies, shown in Fig. 4.1c. The implementation details of the layers, specially PHY and MAC, for UWASN are described in details in later sections of this chapter. The communication between any two modules (two layers) in a *node* is accomplished through two pairs of OMNet++ gates. One pair is used to communicate data messages and the other is used for control messages.

A *node* also has several other auxiliary modules - *utility*, *mobility*, *battery* and *arp*. The *utility* module delivers two main services. Firstly, it exposes a common interface for collecting statistical data related to simulation. Secondly, it functions as a publisher for

parameters that need to be accessed by other modules within a node. *mobility* module dictates the mobility of a *node* or an *object*, any physical body simulated such house, hospital, tree, etc. The *BaseMobility* class provides the basic functions needed in order to model the mobility of a particular *node*. It also provides a random pattern mobility by placing a node at a random position using the update *interval* specified as a parameter for the mobile node. Whenever the position of a node is changed, it notifies and publishes the position to *utility* module so that other modules get the latest position of the node. A number of mobility patterns are available in MiXiM. However new mobility pattern can be implemented by sub-classing the *BaseMobility* and implementing only two virtual methods-namely *makeMove()* and *fixIfHostGetsOutside()*. The *arp* module is an implementation of Address Resolution Protocol (ARP) commonly used to translate the network layer address to MAC layer address. In order to model the energy consumption of a *node*, the *battery* module is used. Different kinds of energy consumption and battery drainage algorithm can be implemented by extending this module.

4.2.3 Connection Manager

Unlike wired simulation, determining the connection between any two nodes in the wireless simulation environment is a challenging task. Since by nature, wireless channel is a broadcast medium, each node in the simulation environment is capable of receiving the transmitted signal theoretically. However due to signal attenuation while transmitting through medium, the power level of the received signal becomes so small for far away nodes that it is impossible for the receivers within nodes to detect the signal. The responsibility of a connection manager in MiXiM is to determine the connectivity between any given two nodes in the network being simulated. The usual way to determine the connectivity among two nodes is to calculate the received signal strength and compare it with the receiver's sensitivity. If the received signal strength is greater than receivers sensitivity, it is assumed that two nodes are connected. However most of the network simulation cases, it is enough to determine the maximum interfering distance of a transmitter with given trans-

mission power. Based on this maximum interfering distance, any given two nodes can be treated as connected or disconnected. An abstract connection manager implementation is included in MiXiM framework called *BaseConnectionManager*. Each NIC of a node in the network is registered to *BaseConnectionManager* at the initialization time through *BaseWorldUtility*. It establishes and removes the connections between nodes by evaluating their the maximum interfering distance. In order to use the *BaseConnectionManager* in the simulation, it must be sub-classed and its only virtual method *calcInterfDist()* must be implemented. Additionally, whenever the position of a node changes, the connection manager is notified by *BaseWorldUtility* through the *mobility* module, consequently it changes the connectivity of the nodes in the network. It is worth mentioning that MiXiM has the capability to support more than one connection types in a single network simulation by using multiple connection manager instances. As an example, GSM and CDMA nodes can be simulated in a single network simulation.

4.3 Physical Layer Implementation for UWASN

Physical layer in MiXiM is not suitable for simulating UWASN, since it is designed mainly for radio framework. In order to utilize MiXiM framework in acoustic channel, one must modify and extend the MiXiM *BasePhyLayer*, *BaseConenctionManager* and *BaseWorldUtility*. The changes required in *BaseWorldUtility* is explained in Section 4.2.1. A simple connection manager is implemented by sub-classing the *BaseConnectionManager* called

ConstantRangeConnectionManager. It determines the distance between two given nodes and compare it with the maximum interference distance provided as a parameter that can be configurable by configuration file (default name of the file is *omnetpp.ini*). Major changes are required for *BasePhyLayer*.

In Fig 4.2, class diagram of *BasePhyLayer* is illustrated. *BasePhyLayer* implements *MacToPhyInterface* and has different aggregate association with *AnalogueModel*, *Decider*

and *Radio* object. Other inheritances and associations related to *BasePhyLayer* are omitted for clarity. Each of these objects is designed as a pure C++ class and it does not represent OMNeT++ module for efficiency (Chapter 2.3). Implementation details of these three classes are described in following subsection.

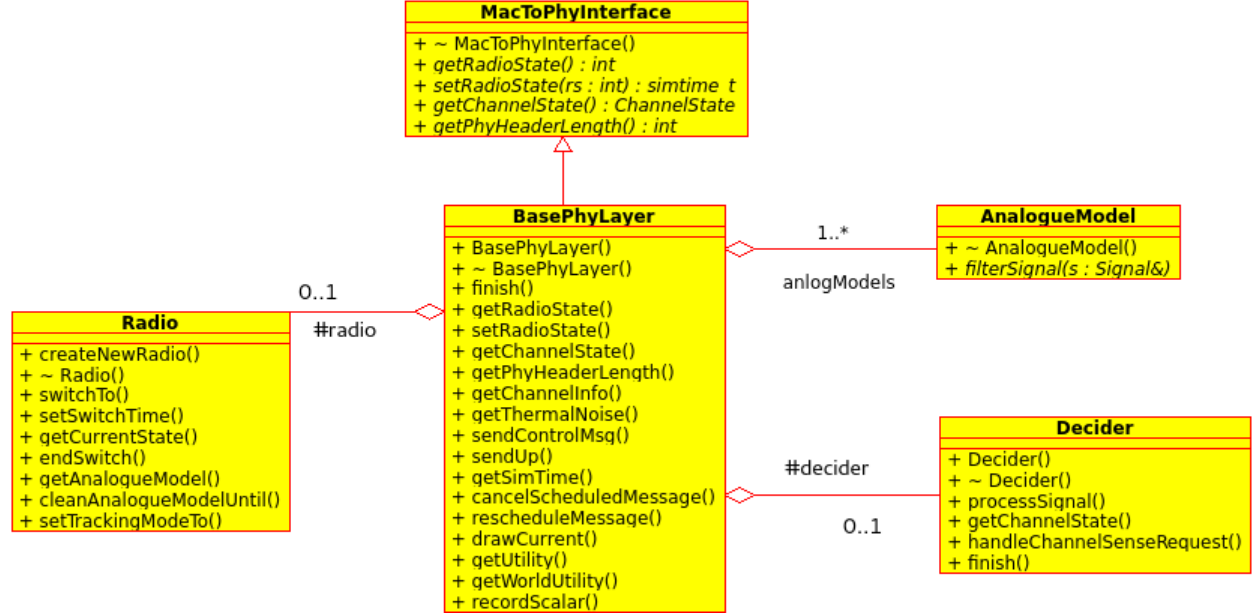


Figure 4.2: Class diagram of *BasePhyLayer*.

4.3.1 Analogue Model for UWASN

The *AnalogueModels* are responsible for simulating the attenuation of the analogue signals passing through the wireless channel; in UWASNs it is the acoustic channel. Each instance of *AnalogueModel* behaves like a filter, every physical signal must be passed through all the *AnalogueModel* instances present in the given receiver. The attenuation in any *AnalogueModel* is represented by a value between 0 and 1; where 1 and 0 imply zero and hundred percent attenuation respectively. It is also used to simulate the different state of a Radio-when Radio is ON state, it calculates 0 attenuation but when Radio is OFF/SLEEP state, it calculates 100% attenuation. The central idea is to calculate all

impediments, a signal experiences in the medium, at the receiver side and apply those attenuations to the received signal. Since the signal attenuation is calculated as a value between 0 and 1, the received signal is just multiplied by the attenuations to determine the actual received signal. As previously mentioned in Chapter 2.3, the signal is represented as a single or multi-dimensional Mapping, so attenuation is also represented as a single or multi-dimensional Mapping. In MiXiM, couple of different implementations of *AnalogueModels* are available for WSNs, but none for acoustic channel. Therefore in order to simulate the acoustic channel attenuation, specially path loss, a new *AnalogueModel* has to be implemented. There are a number of attenuation models for acoustic channels proposed in the literature, Thorpe attenuation model, accepted widely, is used to implement the *AnalogueModel* for UWASNs [8].

Thorpe Attenuation Model

In the case electromagnetic wave propagation, the path loss or attenuation is usually modeled as $A(d) \propto d^{-\alpha}$, where α is a constant factor [47]; it implies that the path loss mainly depends on the distance. On the other hand, in the UWA propagation, the attenuation is a function of both distance traveled and the carrier frequency; it can be denoted by $A(d, f)$. According to [8], the attenuation is given by:

$$A(d, f) = d^k a^d, \quad (4.1)$$

where k is the spreading factor which usually sets 1 for cylindrical, 1.5 for practical, and 2 for spherical spreading, and a is given by

$$a = 10^{\alpha(f)/10}, \quad (4.2)$$

$\alpha(f)$ is called absorption coefficient that can be expressed empirically, using the Thorp's formula which gives $\alpha(f)$ in dB/km for f in kHz as [8]:

$$\alpha(f) = \begin{cases} 3.3 \times 10^{-3} + \frac{0.11f^2}{1+f^2} + \frac{43f^2}{4100+f^2} + 2.98 \times 10^{-4}f^2 & \text{if } f \geq 0.4 \\ 0.002 + 0.11\frac{f}{1+f} + 0.011f & \text{if } f < 0.4, \end{cases} \quad (4.3)$$

4.3.2 Decider Implementation

A decider provides three main functionalities to PHY modeling. First, it decides whether an incoming physical air frame can be treated as a noise or a receivable message. Second, it determines the bit error for the received air frame. Third, it confirms the current state of the channel to MAC through PHY to MAC interface. In real world wireless channel, it is not possible to detect collision among air frames; hence the received signal strength indicator (RSSI) and receiver sensitivity jointly determine whether an air frame can be decoded successfully or not by the given MAC. However, in simulation there is a necessity to determine the different types of collisions such as data-data collision, data-control packet collision, tone data collision, etc.

Deciders present in MiXiM framework are not suitable to detect different type of collisions that affect a MAC protocol. Hence, a new decider design is essential. A generic and extensible decider has been developed for determining different types of collisions in an abstracted way. This decider not only decides whether a collision is occurred but also classifies the collisions into three different classes : *a)* same-type packet collision, *b)* two different-type packet collision, and *c)* multi-type packet collision

The algorithm proposed for the new decider is illustrated in (algorithm 1). When the first bit of an air frame is received by the PHY, it sends the information to the decider to be processed, at this stage the decider just asks the PHY to send the air frame back to it after the reception of whole frame. The decider first, extracts a list of air frames overlapped with one another in the channel during the air frame reception (algorithmic 1, line 2). If only one air frame is present in the list, the decider concludes that there is no collision (algorithm 1, line 4). Otherwise, it infers a collision and starts the process of determining the type of collision. A map of message types as keys and message count as values is created. The algorithm iterates over the air frame list, populate the map with message type found, and increase the count of message type as it finds more messages of the same type. Finally, if the size of the map is found more than 2, it treats the collision as multi-type packet collision. If the size equals 2, it is called two different type packet collision else if the size

Algorithm 1 Pseudocode for CollisionDecider algorithm

```
1: procedure DECIDECOLLISION(start, end)
2:   airFrames  $\leftarrow$  GETCHANNELINFO(start, end)
3:   if size(airFrames)  $\leq 1$  then
4:     collisionType  $\leftarrow$  type : null
5:   else
6:     msgMap  $\leftarrow$  new Map(msgType, msgCount)
7:     add received airframe msgType with msgCount = 1 into msgMap
8:     for i  $\leftarrow 1$ , size(airFrames) do
9:       msg  $\leftarrow$  airFrames[i]
10:      msgType  $\leftarrow$  GETMSGTYPE(msg)
11:      if msgType  $\in$  msgMap then
12:        msgCount ++ for msgType in msgMap
13:      else
14:        add msgType with msgCount = 1 into msgMap
15:      end if
16:    end for
17:    if size(msgMap) = 1 then
18:      collisionType  $\leftarrow$  type : smsgMap[0]
19:    else if size(msgMap) = 2 then
20:      collisionType  $\leftarrow$  type : smsgMap[0] – smsgMap[1]
21:    else
22:      collisionType  $\leftarrow$  type : multi
23:    end if
24:  end if
25: return result  $\leftarrow$  new DeciderResult(collisionType)
26: end procedure
```

equals 1, it is defined as same-type packet collision. At the end of the process, a result object (DeciderResult) is created with collision type and sends up to MAC through PHY to MAC interface (algorithm. 1, from line 6 to 25).

4.4 MAC Implementation

MiXiM provides a basic MAC layer functionalities commonly available in every MAC layer; it is implemented as *BaseMacLayer* module. *BaseMacLayer* provides encapsulation and decapsulation of upper and lower layer packets respectively using the standard addresses. It also provides basic handling of lower layer packets. Basically, *BaseMacLayer* works as a simple ALOHA [3] protocol. In Fig 4.3, class diagram of *BaseMacLayer* is depicted with its inheritance and associations. It exposes six different groups of methods as its public interface.

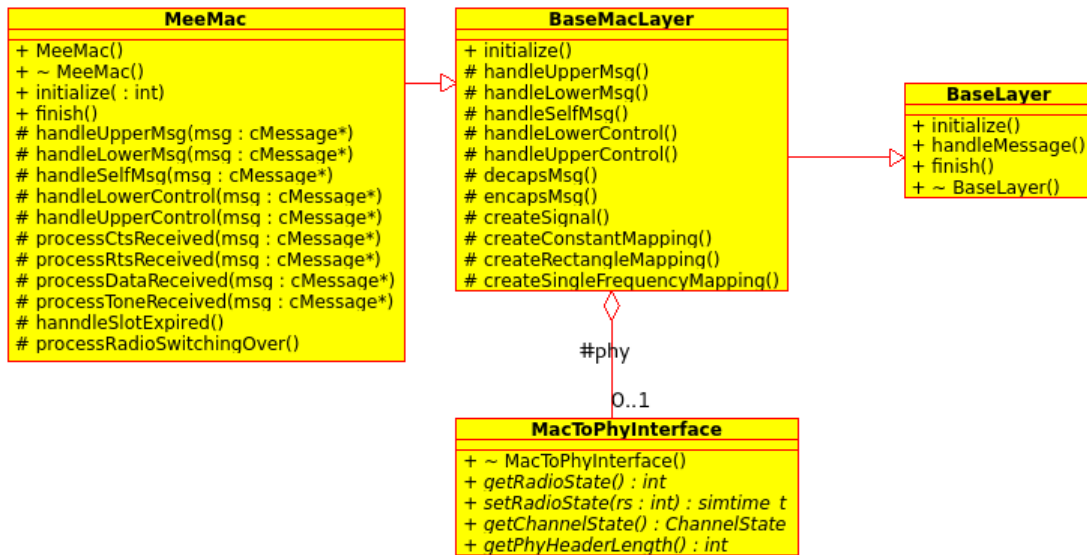


Figure 4.3: Class diagram of *BasePhyLayer*.

Data packet handling The methods of this groups are responsible of handling upper-, lower-, and same layer messages. *BaseMacLayer* provides basic implementation of *handleLowerMsg()* and *handleUpperMsg()* methods, but it does not provide any

implementation for *handleSelfMsg()* ; a sub class must implement this method according to it's need.

Control packet handling Like the previous group, it provides mechanism of handling control packet between upper and lower layer. However *handleUpperControl()* is a pure virtual function, a sub class must implement this method, otherwise the simulation cannot not be compiled.

Packet encapsulation and decapsulation Method *encapsMsg()* and *decapsMsg()* are responsible for encapsulation and decapsulation of upper and lower layer packets respectively.

Signal creation It provides several methods to create the Signal (Ref. Chapter 2) for physical layer. Most of the time sub-class does not require to override these methods.

Radio switching Methods of this group are used by MAC layer to control Radio switching. It consists of two methods: *getRadioState()* and *setRadioState()*, those in fact are inherited from *MacToPhyInterface*.

Channel status This interface group is used by MAC layer to get the current state of the channel. Only one method, *getChannelState()* is exposed from *MacToPhyInterface* for this purpose.

In *MeeMAC* protocol implementation, the methods belong to signal creation, radio switching, and channel status groups have not been overridden, since these methods are usually not affected by specific MAC algorithm. The rest of the methods have been overridden by *MEEMAC* protocol implementation as well as a number of public methods have been exposed by *MEEMAC*. Those exposed methods can be grouped into three different groups. Each group represents a specific type of event handling, described below.

Packet received event handler Whenever a packet arrives successfully from PHY layer, the corresponding event specific to the packet-type received has been fired as a callback method. This facilitates to implement custom algorithm based on the event. The

methods of the group are *processToneReceived()*, *processRtsReceived()*, *processCtsReceived*, and *processDataReceived()*.

Radio switching event handler This group has only one callback method called *processRadioSwitchingOver()*. It is fired whenever any switching event is occurred in the Radio. This call back method can be utilized to calculate the statistics of related to radio-switching and it's energy consumption.

Time slot expired event handler *MEEMAC* is a synchronized protocol in which the transmission of any type is only occurred at the beginning of a slot. In order to create the logical time slots of specific duration, a timer function has been scheduled at the initialization phase of the protocol. The duration of the slot is calculated based on the maximum propagation between any two nodes in the network. Currently, MiXiM provides three type of timers: 1. *SimpleOneShotTimer* 2. *RepeatTimer* and 3. *FrameTimer* . For higher performance and accuracy, *SimpleOneShotTimer* is used to simulate the time slots. Whenever a time slot is expired, the callback function, *handleSlotExpired()* has been called.

Utilizing above mentioned interface methods, *MEEMAC* protocol is implemented as state machine depicted in Fig 3.4. The next state of the state-machine depends on two parameters: the current state of the machine and the type of the event fired. As an example, if the state-machine is at *Expecting* state and the slot expire event is occurred, the next state would be set *Idle*. By extending this simple interface, any kind of synchronized MAC protocol can be implemented. A number of MAC protocols, ST-Lohi, S-FAMA and ESFRA [44]; are implemented using this framework.

Chapter 5

Simulation Results and Evaluations

In this chapter, both the proposed protocol and the T-Lohi protocol are simulated under similar conditions to demonstrate the effects of the improvement achieved with the proposed protocol. This research also simulated the S-FAMA protocol and compared it with the proposed protocol. In this research the OMNET++ [64] was used as a network simulation platform and modify the MiXiM [33, 67] framework to make it suitable for an underwater acoustic sensor network. MiXiM is an OMNeT++ modelling framework created for mobile and fixed wireless networks (wireless sensor networks, body area networks, ad hoc networks, vehicular networks, etc.). It offers detailed models of radio wave propagation, interference estimation, radio transceiver power consumption and wireless MAC protocols (e.g., Zigbee) [66].

5.1 Experimental Setup

Star topology is adopted to demonstrate the effect of hidden nodes on the proposed protocol and the T-Lohi protocol. Star topology is utilized in simulations to simplify and identify hidden nodes precisely. In this simulation set-up, every node can communicate with the center node (sink) and is hidden to all other nodes. That allows this simulation to control the number of hidden nodes. Sensor nodes are deployed in a three dimensional space with a height, width and depth that are 1200 meters (m) each. The sink (center) node is situated

at the origin, and the source nodes are deployed on the X, Y and Z axes. Simulations have been performed for different number of nodes in the network. Each source nodes position is uniformly distributed and bounded along the corresponding axis such that each node must be out of interference range of other source node/nodes as shown in Fig. 5.1. The S-FAMA protocol has been also simulated exploiting the same network topology and parameters in order to compare and evaluate the proposed protocol with RTS-CTS based protocol, i.e., S-FAMA.

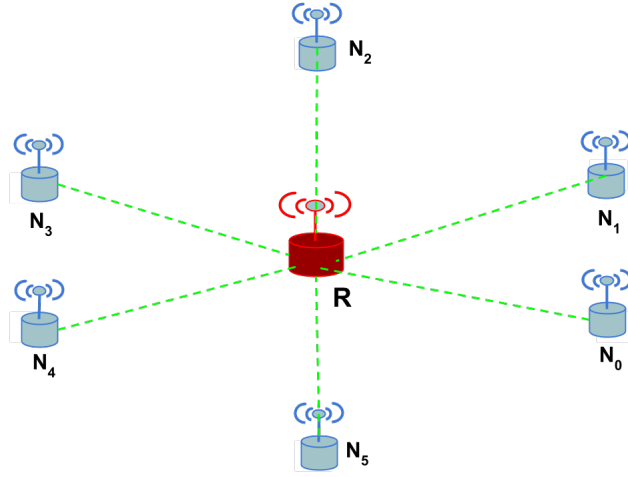


Figure 5.1: Network topology used for simulation.

5.2 Protocol Parameters

In order to maintain fair comparison between the two protocols (proposed and T-Lohi protocols), this research kept the values of the protocol parameters the same as had been used in [55]. The simulation time for each run is 500 seconds. The payload size is 650 bytes and header length of each layer (from application to physical) is fixed to 5 bytes and the length of CTS and RTS packets are 10 bytes. Each node's application layer generates packets according to Poisson distribution with a mean arrival time equal to $\frac{1}{\lambda}$. For each $\frac{1}{\lambda}$ value, 250 simulation runs are performed and the average of the runs is

reported. The maximum transmission power of the acoustic modem is set to 2 watts and the maximum interference range is 500 meters. The acoustic channels path loss is calculated using Thorpes model [8]. The acoustic modem data transmission rate is assumed to be 8000 bps. Furthermore, all nodes are assumed to be static during each simulation run. Protocol and acoustic modem parameters are listed in Table 3.1 and Table 3.2, respectively.

5.3 Results for Single-hop Star Topology

Fig. 5.2 shows the effect of hidden nodes on the channel utilization of the T-Lohi protocol. Solid lines in the graph represent the channel utilization of the T-Lohi protocol with respect to the offered load (number of packets/sec.) where all nodes in the network are connected with one another and packets are sent to a single receiving node, whereas dashed lines represent the channel utilization of the T-Lohi protocol for multi-hop networks with hidden nodes. The simulation's results show that the T-Lohi protocol performs well when there are no hidden nodes, however, it suffers data packet losses when hidden nodes are present in the network. The performance of the T-Lohi protocol exhibits similar behavior as found in the Aloha where performance increases to a maximum peak and then drops sharply with increasing traffic load. This indicates instability in the protocol even when the packet rate is as low as 0.5 packets/sec. Moreover, it is important to note that even having one hidden node in the network degrades the peak channel utilization by 50 percent compared to the no hidden node scenario. This research's observations indicate that this performance loss is due to data-data and tone-data collisions in the presence of hidden nodes in the network.

Fig. 5.3 shows the comparison of channel utilization between the proposed protocol and the T-Lohi protocol when there are hidden nodes present in multi-hop networks. Solid and dashed lines represent the proposed protocol and the T-Lohi protocol, respectively. First, the proposed protocol does not exhibit instability and the performance does not decrease with increasing traffic load in the presence of hidden nodes. The peak channel utilization of

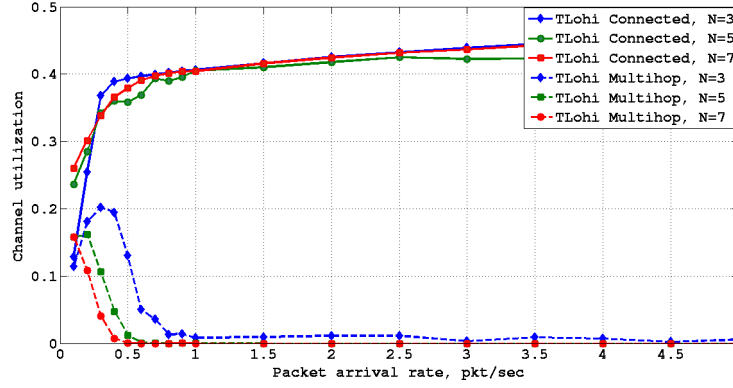


Figure 5.2: Effect of hidden nodes on T-Lohi MAC protocol.

MEEMAC protocol is at least twice of that of the T-Lohi protocol (0.2 and 0.4 for T-Lohi and MEEMAC respectively for packet arrival rate equals to 0.5). This is a clear indication that the proposed protocol successfully mitigates the impact of hidden nodes in the network using hidden-link control mechanism.

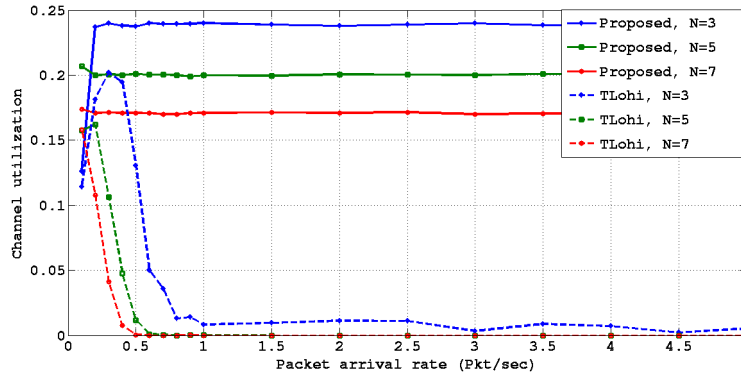


Figure 5.3: Comparison between the T-Lohi protocol and the proposed protocol.

Fig. 5.4 depicts the comparative evaluation of channel utilization between the proposed protocol and the S-FAMA protocol. MEEMAC protocol shows better channel utilization as the number of hidden nodes increases. As the number of hidden nodes in the hidden collision domains increases, the probability of RTS/CTS collisions increases significantly since the potential transmitting node contends with the nodes from local and the hidden

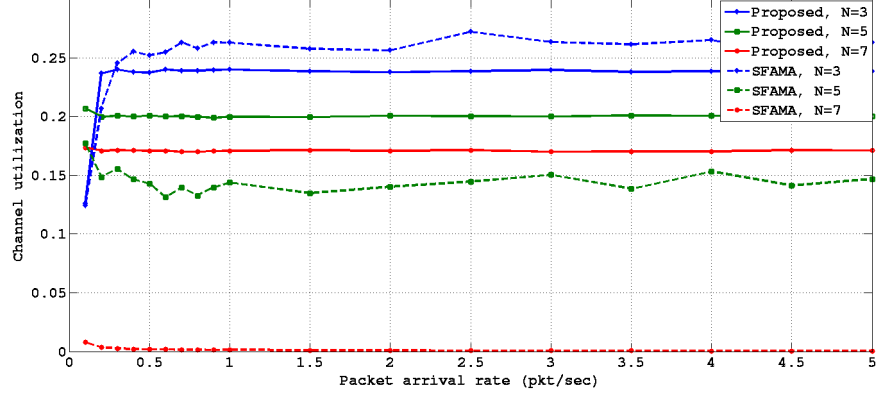


Figure 5.4: Comparison between S-FAMA and the proposed protocol.

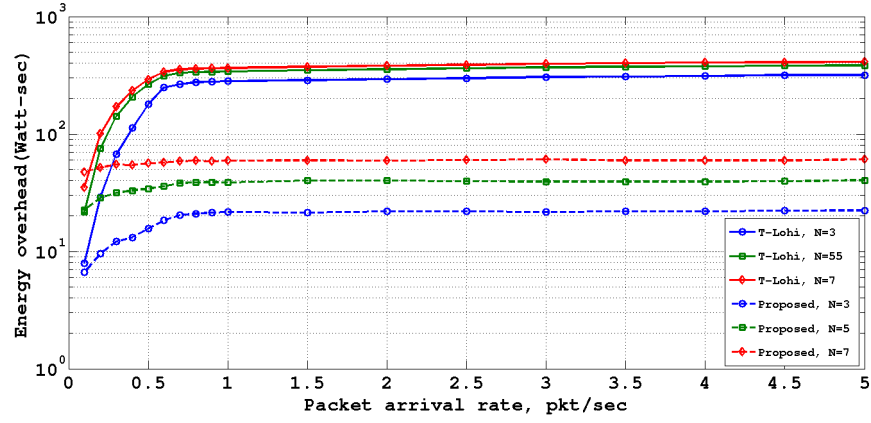


Figure 5.5: Comparison of energy overhead between the T-Lohi protocol and the proposed protocol.

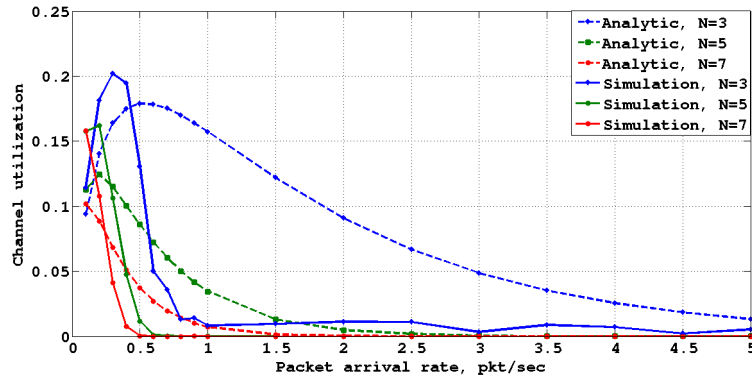


Figure 5.6: Simulation vs. quantitative analysis for the T-Lohi protocol.

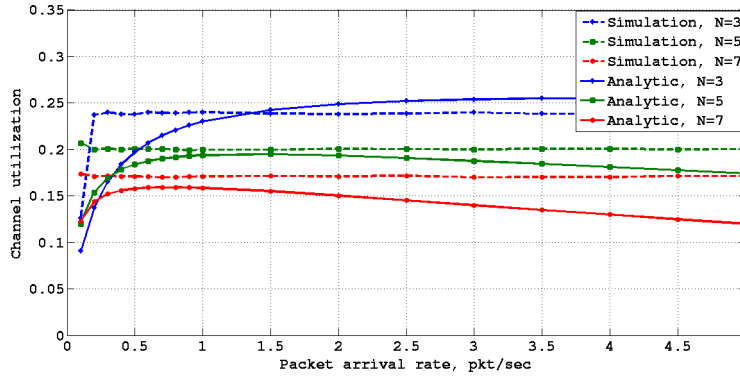


Figure 5.7: Simulation vs. quantitative analysis for the proposed protocol.

collision domains simultaneously. In contrast, the proposed protocol cuts off the contending nodes from the local collision domain during the local-link reservation phase. Consequently the collisions between notifications packets in the later phase have been significantly reduced, which results in better channel utilization for the proposed protocol than S-FAMA protocol. It is worth mentioning that if the number of hidden nodes in the networks is very low such as one, the S-FAMA outperforms MEEMAC protocol. The main reason for this is the additional local-link reservation is needed for MEEMAC.

Simulation output of energy overheads for the proposed protocol and the T-Lohi protocol are shown in Fig. 5.5. As expected, the proposed protocol provides much better performance than the T-Lohi protocol. The energy overhead of the T-Lohi protocol is two orders of magnitude higher than the proposed protocol. Therefore, the proposed protocol works as an energy-efficient MAC protocol.

In Figs. 5.6 and 5.7, comparisons of simulation and quantitative analysis results, e.g., channel utilization, are shown for both the proposed protocol and the T-Lohi protocol respectively. From the graphs, it can be observed that there is no significant difference in the trends between simulation results and that of analytical results. The analytical results provide better performance but the simulation results represent more realistic results. The small discrepancies shown in the graph is because in the analytical model couple of assumptions have been made.

By evaluating the proposed protocol through quantitative analysis and simulation, it can be stated that the proposed protocol outperforms in terms of energy efficiency, channel utilization and end-to-end delay. The proposed protocol achieves stable throughput even during a high traffic load whereas existing protocols become unstable and do not perform well. Additionally, the proposed protocol achieves better energy efficiency (at least to one order of magnitude) and lower end-to-end delay (at several orders of magnitude).

5.4 Results for Multi-hop Star Topology

In order to simulate multi-hop network, multi-hop star topology where the nodes are distributed in 4x4 kilometer area has been used. The sink node is situated at the center of the simulated area and the source nodes are at the ends of the area. All other nodes between the sources and the sink work as relay nodes. Three different scenarios consist of 2, 3 and 4 hops between the sources and the sink (i.e. 9, 13 and 17 nodes respectively) in the network have been applied but in each scenario the number of source nodes are kept to four, as shown in Fig 5.8.

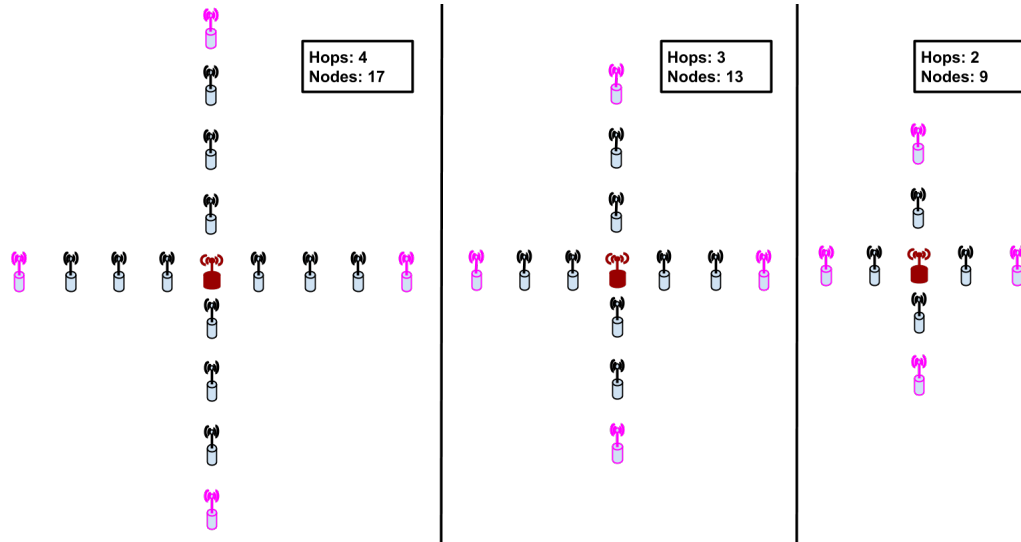


Figure 5.8: Multi-hop star topologies used for simulation.

In each scenario, mean packet success-rate and end-to-end delay of the network have been measured. Packet success-rate (P_s) is defined as the ratio of average number of successful data packets received by the sink node (in application layer) to the average number of packets generated by all the source nodes (in the application layer). End-to-end delay is defined as the ratio of the measured average end-to-end delay of the successful received packets to failure-rate ($1 - P_s$) [59]. In other words, the success-rate represents the probability of successful reception of a data packet generated in the source. The measured end-to-end delay is the delay calculated at the sink when a data packet is successfully received by the sink. It is the time difference between packet generation time and the packet reception time. It is important to note that each iteration of the simulation has been run for 500 seconds and the mean has been calculated using 250 samples (iterations).

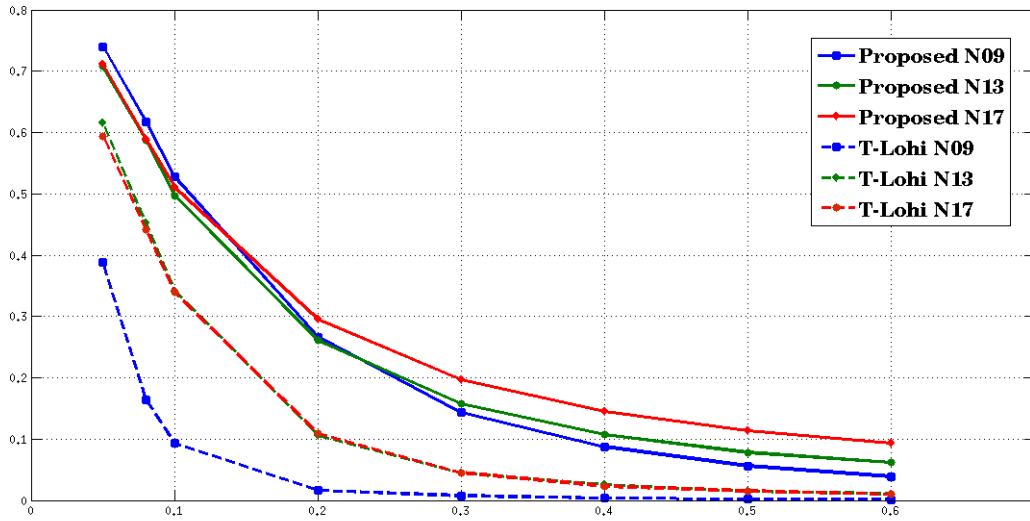


Figure 5.9: Success ratio (success probability) vs. arrival rate for multi-hop network.

The success rate of the proposed protocol and the T-Lohi protocol has been depicted for different packet arrival rate in Fig 5.9. It is evident that as the packet arrival rate increases, the success-rate for both protocol decreases, however, for the T-Lohi protocol, it decreases with a higher rate. Moreover, as the number of hops between the source and the sink increases, the effect of increasing hops adversely impact on success-rate of the

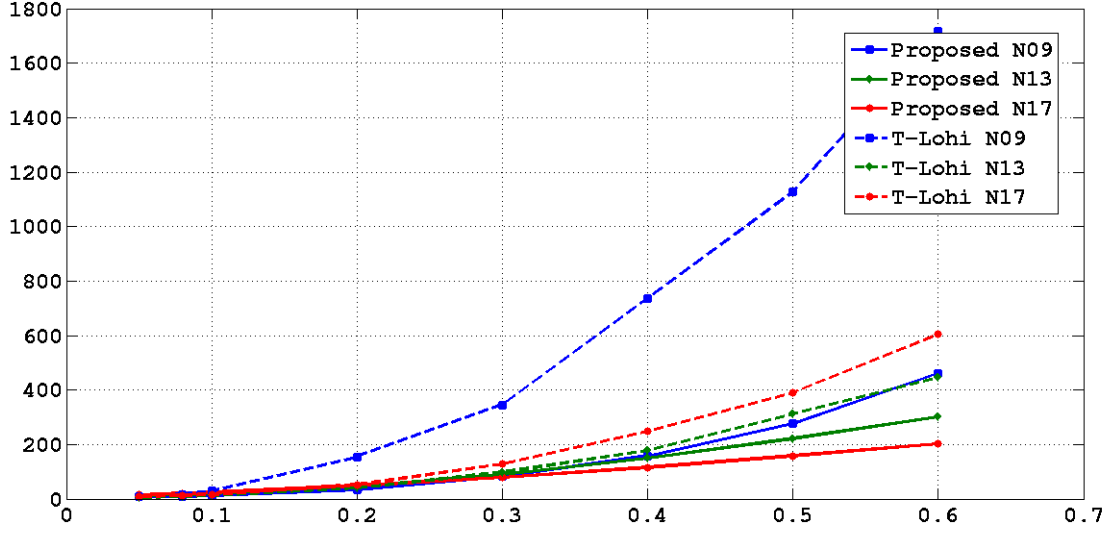


Figure 5.10: End to end delay vs. arrival rate for multi-hop network.

T-Lohi protocol while the proposed protocol demonstrates a very consistent and stable success-rate.

Similarly, with respect to the end-to-end delay, the T-Lohi protocol experiences a couple orders of magnitude higher end-to-end delay compared to the proposed protocol. The corresponding graph is shown in Fig 5.10. Although both protocols undergo similar pattern increasing delay with respect to the increasing packet arrival rate, the T-Lohi protocol experiences unbounded delay.

By evaluating our proposed protocol through quantitative analysis and simulation, we find that the proposed protocol outperforms others in terms of energy efficiency, channel utilization and end-to-end delay. The proposed protocol achieves stable throughput even at high traffic load while existing protocols become unstable and do not perform well. Besides that, the proposed protocol achieves better energy efficiency (at least one order of magnitude) and lower end-to-end delay (several orders of magnitude) compared to other existing protocols.

Chapter 6

Conclusion and Future Research Direction

This thesis presents an energy efficient MAC protocol called MEEMAC for UWASNs based on a novel two phase contention resolution technique. The major sources of energy loss in multi-hop UWASNs are data packet collisions, idle listening, over hearing and protocol overhead. The MEEMAC eliminates data packet collisions by reserving the channel prior to any data transmission and by inhibiting other potential interfering nodes from transmission until the transmitted packet has successfully arrived at its destination. It also reduces the idle listening by utilizing low power wake-up tone receiver. The main data receiver is kept in sleep mode most of the time and it is awakened only when required by the wake-up tone receiver. It also reduces overhearing by keeping the unintended nodes in sleep mode. Moreover, in order to minimize the protocol overhead, a short length tone instead of a packet is used to reserve the channel. This thesis also presents a probabilistic model of the proposed MAC protocol. It facilitates determination of channel utilization, energy consumption and end-to-end delay of the protocol in different network scenarios. It also leverages to evaluate the proposed protocol with two competing existing MAC protocols for UWASN namely the T-Lohi protocol and the S-FAMA.

In this thesis, the design of a simulation framework for MAC and physical layer is presented. It is demonstrated that a number of MAC protocols can be implemented based on this framework, such as MEEMAC, T-Lohi [55], S-FAMA [37] and ESFRA [44]. The

Thorpe acoustic channel model is also incorporated into the framework as the underlying physical channel for the UWASNs simulation.

Finally, the the proposed MEEMAC protocol is evaluated with two competing MAC protocols T-Lohi and S-FAMA which are implemented by utilizing both the developed probabilistic model and the simulation framework. It is observed that the MEEMAC achieves higher energy efficiency, channel utilization and end-to-end delay. For example, in a medium load traffic, the energy overhead of the T-Lohi protocol is two orders of magnitude higher than the proposed protocol. It is found that the peak channel utilization of the proposed protocol is at least 50 percent more than that of the T-Lohi protocol. Similarly the MEEMAC protocol achieves approximately 30% more channel utilization than the S-FAMA in a medium load traffic.

In the future, several enhancements can be made to MEEMAC protocols. Firstly, in MEEMAC, all nodes need synchronization which requires extra overhead. MEEMAC protocol can be utilized in an unsynchronized environment by extending the slot duration twice of its current length as proposed in FAMA [23]. The outcome of this change is worth exploring. Secondly, different types of back-off strategies can be studied for the MEEMAC protocol. In this thesis, only uniform distribution was used to calculate the back-off time. A sophisticated back-off mechanism can provide better collision avoidance among tones and control packets. Thirdly, an optimum algorithm can be devised for prioritizing CTS packets when an intended receiver has to deal with multiple RTSs in order to provide spatial fairness and to increase the overall channel utilization. Fourthly, data streaming (multiple data packet transmission for a single reservation) technique can be studied to establish its impact on protocol fairness, energy and channel utilization. Finally, a prototype implementation of MEEMAC protocol can be implemented

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